A Thesis

entitled

Identification of Sewage Sludge Injection Application on Harvested Agricultural Fields Using Landsat TM Data

By

Yitong Jiang

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Arts Degree in Geography

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An Abstract of

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Application of sewage sludge to agriculture fields is used by farmers to improve the soil conditions, physically, chemically and organically. However, it has potential risk to public health and the environment because of the heavy metals, nutrients and pathogens that may be included in biosolids. The location of all applications of sewage sludge is not known because some records of application are missing. Remote sensing technology has been shown to be an effective way to detect surface application of sewage sludge on agricultural fields for different times of year over large areas. The main objective of this study is to determine if Landsat TM data can be used to identify harvested agricultural fields that have had sewage sludge applied through injection. The spectral characteristics were compared between sewage sludge injection applied fields and control fields, including the following spectral ratios: R(7,5), R(5,4) and R(3,2). Landsat TM images from path 20, row 31 from 2003 to 2007 were selected in this study, and the sewage sludge injection application data in Oregon, Ohio were mapped with the images. The results show that there are spectral differences between fields that had sewage sludge injected and control fields that have not received sewage sludge. Band 4, band5 and band 7 show more differences than other bands. The differences are detectable up to 10 to 18 days after sewage sludge injection. The ratio combinations of R(7,5), R(5,4) and R(3,2), respectively, in blue, green and red can be used to identify sample sewage sludge application fields through injection. The fields with sewage sludge injected appear gray, and the control fields appear yellow. A pixel from a ratio combination image is representing a spot in sewage sludge injected fields, when it meets all the three conditions: R(3,2) value is in the confidence interval of 1.651 to 1.665, R(5,4) value is in the confidence interval of 1.941 to 1.981, and R(7,5) value is in the confidence interval of 0.561 to 0.569, at 95% confidence level.

Key Words: Landsat TM, remote sensing, sewage sludge, biosolids

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Chapter 1

Introduction

Research shows that the application of sewage sludge as a soil amendment on agriculture fields can increase the production for several crops, (Reddy et al., 1989) by renewing the constitution of physical, chemical and organic properties of soil (Wei et al., 1985; Sommers, 1977; Epstein et al., 1975). Application of sewage sludge on agriculture fields is also better for the environment than dumping it into the oceans, rivers, lakes, and bays (Clapp et al., 1977; Bastian, 1997).

It was common to dump sewage sludge into the ocean before 1980s (Weis, 1988). This practice has ended in many nations by national and international laws and regulations. In 1991, the Congress of the U.S. stopped the ocean dumping of sewage sludge; and the U.S. Environmental Protection Agency (US EPA) brought a new policy to encourage the application of sewage sludge on agricultural fields. Sewage sludge is also called "biosolids", because it is “solids produced by biological activity” (US EPA, 1994). With the promotion of sewage sludge land application and the improvement of wastewater treatment technology, the waterways are now cleaner and safer for recreation and seafood harvest.

However, the practice of applying biosolids to agricultural fields could have a potential risk for public health. Though sewage sludge has been treated in wastewater treatment plants, it still contains heavy metals, nutrients and pathogens. (Weis, 1988; Khuder et al., 2007; Khuder et al., 1998). Heavy metals (such as copper, lead and zinc), pathogenic bacteria, nutrients and toxic chemicals may cause diseases such as asthma, migraine headaches, allergies, bronchitis, upper respiratory infection and gastroenteritis (Khuder et al., 2007; Weis, 1988; Khuder et al, 1998). Runoff of animal waste, fertilizers and biosolids from farm fields can contribute excessive nutrients to a lake or other body of water. Those nutrients can cause a dense growth of algae, while the decomposition of algae depletes the supply of oxygen, leading to the death of animals. Plus, the unsafe pathogens can also contaminate the soils and crops. Within soil, the way chemicals interact with ecology system and wildlife is a fairly new science. The "accumulation of heavy metals within food webs" and their "persistence in the environment" is somewhat unknown (McBride et al., 2007). Therefore, application of sewage sludge on agriculture fields may be detrimental to local ecosystems and public health.

As documented, the state-wide average sewage sludge application rate in Ohio was more than 60%. The sewage sludge that applied to agricultural fields is 90% of the total production from Northwest Ohio (Wu, 2007). Therefore, researchers from the University of Toledo, Bowling Green State University, and University of Michigan, in fields such as public health, environmental science, ecology and geography are working together to analyze potential health and environmental impacts from application of sewage sludge in the USDA project named *Monitoring Agricultural Sewage Sludge Application in Ohio*. The group has published a paper on the epidemiological study. Researchers correlated sewage sludge application to illness in a database (Khuder et al., 2007). This first study used permitted fields only to test the hypothesis that sewage sludge may cause illnesses. One-mile buffer from the permitted fields were drawn to divide the residents into exposed and unexposed groups. Khuder et al. (2007) compared the “reported symptoms, distribution of chronic diseases, distribution of acute diseases” between the two groups, and logistic regression for the “frequency of occurrence of acute disease” and “actual distance from the permitted fields” was analyzed. The statistical results showed that some symptoms were related to the exposure to sewage sludge application, including “excessive secretion of tears, abdominal bloating, jaundice, skin ulcer, dehydration, weight loss, and general weakness”. Moreover, the results for “exposed group” were similar to previous research for sewage workers (Khuder et al., 2007). A criticism of Khuder et al. (2007) was that actual application data was not used to develop the statistics for the analysis. A complicating factor in assessing the cause and effect between biosolids application and human health is the difficulty in getting a complete record of sewage sludge application.

To improve the epidemiological health survey, we need to know where sewage sludge has been applied. The sewage sludge application records are kept by Ohio EPA, Waste Water Treatment Plants and the applicators. Nine boxes of hard copy documents record sewage sludge application activities in Lucas, Wood, Marion, Ottawa, Putnam, Henry, Hancock, Sandusky, Seneca and Fulton Counties, from 1980s till now, including the annual site status reports for each year, annual application records, multi-component analysis and complaint letters.

The application records are kept as hard copies. The actual date that the application occurred on is not known. Records of application dates before 2002 were not accurate with the dates given as January 1, 2001 and finished on December 31, 2001. For some dates, the application details are not specific. For instance, on field 13A, application started on August 28, 1990 and finished on October 31, 1990. Sewage sludge application on a field does not realistically last for a year or even several months; it usually takes several days to a week depending on the area of the field and the application process. Thirdly, the documents that saved by the Wastewater Treatment Plants (WWTP) are not uniform. Some plants recorded the amount of 10 metals in soil compared with the amount of sewage sludge application, such as arsenic, cadmium, chromium, copper, lead, mercury, molybdic, nickel, selenium and zinc. Some plants only recorded five metals, such as cadmium, copper, lead, nickel and zinc. The units for metals are different, measured as lbs/acre, lbs/ton, or mg/kg. Plus the typeset of the forms is different from year to year. Finally, it is hard to locate some of the fields based solely on the section number and the intersection of two roads, which is the common way it is written on the forms. Moreover, the field ID from OH EPA and the WWTP are different. Therefore, some sewage sludge application data are missing.

Considering the potential harmful effects due to the large amount of sewage sludge application, and the spotty nature of the application records, an effective way to detect sewage sludge applications is needed. Remote sensing technology has become an economical method to detect and map the physical and chemical constitutions of surface soil (Dematte et al., 2003). One Landsat image has a swath width of 185 km, which covers a multi-county area. For example, Lucas, Ottawa, Wood, Henry, Putnam, Paulding, Defiance, Williams and Fulton counties are covered by part of Path 20 Row 31 Landsat image with hundreds of sewage sludge application fields are located within that scene.

Landsat comes the same scene every 16 days. Moreover, changes in soil texture, components, humidity and temperature by the application of sewage sludge could be detected by certain bands of Landsat images. Dr. Sridhar of Bowling Green State University (BGSU) successfully identified the surface sewage sludge application on winter wheat stubble fields using Landsat TM images and remote sensing technology in 2006. He applied spectral ratio combinations of R(7,5), R(5,4) and R(3,2), displayed in the blue, green and red, respectively. In the ratio combination images, the fields with sewage sludge treated appeared gray, and the control fields appeared yellow (Sridhar et al., 2006). Then, he mapped the total phosphorus concentration of biosolid amended surface soils in 2009 (Sridhar et al., 2009).

The main objective of this thesis is to determine if the method used by Sridhar et al. (2006) for identifying sewage sludge surface application can also be used to identify the agricultural fields where sewage sludge has been injected. To address this objective, pixel values from band 1 to band 5 and band 7 for both the study fields and control fields were extracted from the Landsat TM images and were plotted to compare the differences between each band. The spectral ratio combinations of R(7,5), R(5,4) and R(3,2), display in blue, green and red, respectively, were then used to develop an operational technique. False color images were used to test the ability to monitor sewage sludge application on harvested agricultural fields.

Chapter 2

Background

2.1 Sewage Sludge

Sewage sludge is the product of the wastewater treatment process, for it contains solid organisms and it is also called biosolids (US EPA, 1994). The contaminated elements can be removed by wastewater treatment through series of technical operations, such as "thickening, dewatering, aerobic digestion, anaerobic digestion, and alkaline stabilization" (Turovskiy et al., 2006). After those treatment steps, sewage sludge can be used as soil amendment to supply nutrients and optimize the structure for soil.

In Europe, sewage sludge has been used in agriculture for decades. The European Council promotes the use of sewage sludge in agriculture. Because the land application of sewage sludge improves soil condition in many ways (European Council, 1986; European Council, 1991). But many people fight against the practice of land application. They argue that the potential risk to public health due to the sewage sludge application can not be ignored, no matter how beneficial it is to the soil. Therefore, the European Council put a lot of efforts on the protection of the environment and soil, where sewage sludge is applied (European Council, 1986). And European industries have also being supportive by reducing the toxic materials in the factories. For example, Cadmium, which can cause cancer, has been largely reduced in sewage sludge in Europe today.

A similar history of sludge also took place in China. Application of waste to farm fields is the most natural and oldest way to fertilize the crops in China. In the past, the sludge was not treated. Even today, some farmers still apply the waste from their own household to their own land in the country of China. However, with the development of the heavy manufactory and bio-chemical industry, the application of untreated sewage sludge onto farm land can result in diseases transmission and environmental pollution. Therefore, the completed legislation and regulation system about land application of sewage sludge in China needs to be made as soon as possible (Wang, 1997).

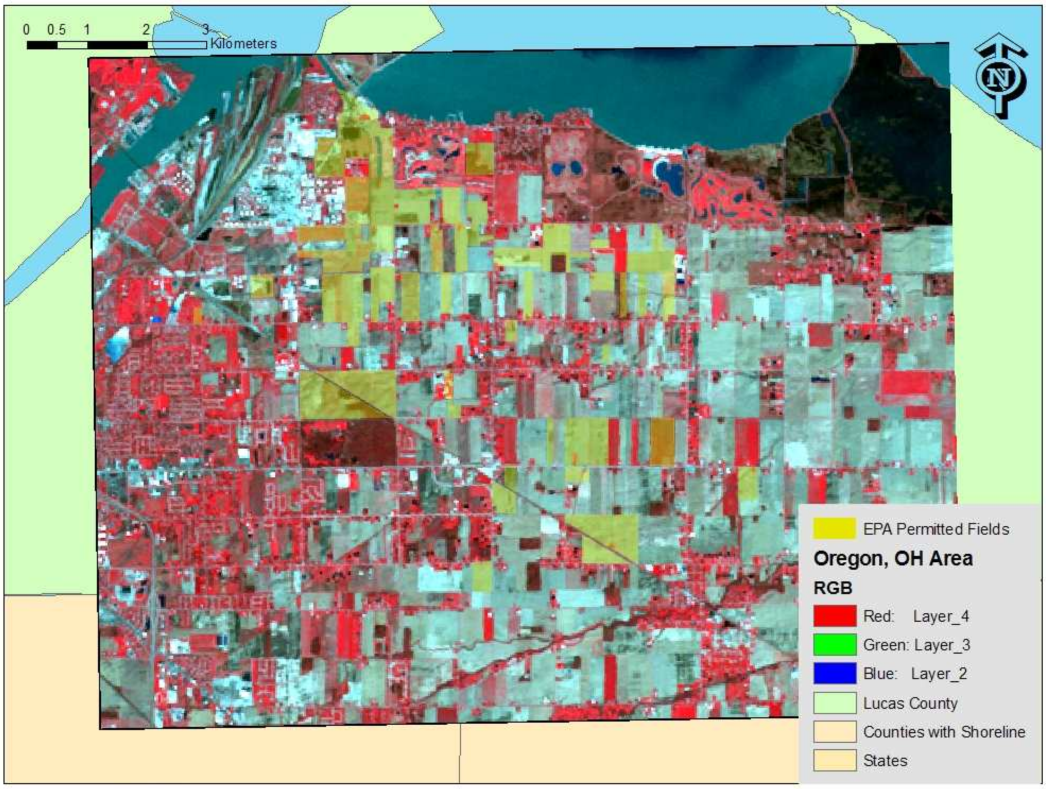
In the United States, 40 Code of Federal Regulations (CFR) Part 503 is the final version of sewage sludge regulation. Sewage sludge land application was defined as "spreading, spraying, injecting, or incorporating sewage sludge onto or below the surface of the land as a soil amendment, not only to improve the structure of the soil, but also to supply nutrients to crops and other vegetation grown in the soil" (US EPA, 1994). Sewage sludge can be applied to agricultural fields, forests, reclamation sites, public contact sites, lawns, and home gardens (US EPA, 1994).

To make sure that sewage sludge is used in a way that protects human health and the environment, 40 CFR Part 503 lists requirements for the land application, surface disposal, and incineration of sewage sludge (US EPA, 1993). For land application, the manual provides detailed guidance to the sewage sludge producer, land applicator, land owner, regulator and record keeper (US EPA, 1993).

According to the regulations, sewage sludge for land application is categorized into Class A and Class B, based on the amount of pathogen in it and the stability. Class A sewage sludge has to meet very tough treatment standards, while Class B sludge has to meet strict application permits requirements. No pathogens are allowed to be detected in Class A sewage sludge. It has to meet strict vector attraction reduction requirements, which means the nature of sludge needs to attract insects and other transmission agents need to be reduced. The metal concentration in Class A sewage sludge needs to be controlled below certain level. Class B sewage sludge is also treated, but it is allowed to contain detectible levels of pathogens. Since Class B sewage sludge is not as safe as Class A, people are not allowed to contact it directly (Rüdiger, 1998; Harriso, 2002). Permitted fields' records, buffer requirements, public access requirements, and crop harvesting restrictions are needed when Class B sewage sludge is applied (US EPA, http://water.epa.gov/polwaste/wastewater/treatment/biosolids/genqa.cfm).

In the US, of all the sewage sludge that applied on farm land, more than half of it is Class B sludge (Lewis et al., 2002). Ohio EPA follows the federal regulation, and permits the application of Class B sewage sludge to agricultural fields. In Ohio, 328,857 tons of sewage sludge was disposed of in 2006 (Rader, 2008), more than 40% of it was land-applied, less than 40% was Class A, and more than 60% was Class B (Rader, 2008). In northwest Ohio 42,554 tons of sewage sludge was disposed of in 2006, more than 50% was Class B (Radar, 2008).

Splash and injection are common biosolids application methods (Wang, 2009). In Bowling Green, Ohio, the sewage sludge is applied as a 3% biosolids and 97% water liquid on the surface of the fields as shown in Figure 2-4, which is the most common and least expensive application method (Wang, 2009). Splash is also called as surface application. Sridhar et al. (2006) and Wang (2009) concentrated on the identification of sewage sludge surface application on winter wheat stubble fields. The WWTP of the City of Oregon use the injection method (Figure 2-6) to apply sewage sludge to its agricultural fields (Wang, 2009). Sewage sludge is injected 10 to 12 inches below the field surface, which reduced the spread through wind and insects. This study is focus on monitoring the injection application of sewage sludge on harvested agricultural fields.



Yitong Jiang Aug. 29, 2010
Data Sauce: Project of Remote Sensing Monitoring of Agricultural sewage sludge application and possible Health Effects

Figure 2-1: Landsat 5 image from April 18, 2005 with EPA permitted fields in Oregon, OH highlighted in yellow

2.2 Project Description

Followed is a brief description of the USDA project of *Monitoring Agricultural Sewage Sludge Application in Ohio*.

Figure 2-2: Teella, Obed, Josh, Paul, Abhi, Amie, Yitong and Mike were collecting air quality field data to use for validation of prediction parameters in the sludge project.

In 2010, this project published a chapter about “Application of GIS in Evaluating the Potential Impacts of Land Application of Biosolids on Human Health” in the book *Geospatial Technologies in Environmental Management, Geo-technologies and the Environment 3* (Czajknowski et al., 2010). This chapter shared the use of spatial analysis in a public health and environment study. The locations of Class B biosolids permitted and application fields, the data of “microorganisms, metals, and pharmaceutical and personal care products (PPCPs)" from samples in Wood, Lucas and Greene Counties, Ohio, were put together in a Geographic information system (GIS) with remote sensing imagery. The epidemiological survey performed by Khuder et al. (2007) was mapped in this study too. The chapter summarized the research of the group and prepared the dataset for the future spatial analysis and health survey.

An evaluation of the change in mental concentration at an agricultural field land applied with class B sewage sludge in northwest Ohio was done by Rader (2008) as her Master's thesis. Which metals were accumulating in field at what rate due to the sewage sludge land application was investigated. By examining the samples in laboratory, she found that the concentrations of cadmium, chromium and zinc were not related with sludge application, but the concentrations of copper (16mg/kg), lead (18mg/kg) and nickel (2.9mg/kg) were higher in the treated field than the nearby control field.

Researchers in environmental sciences have also examined the pharmaceutical compounds in the wastewater process stream in Northwest Ohio (Spongberg et al., 2008), and determined the persistence of pharmaceuticals in biosolids and surface water using liquid-chromatography tandem mass spectrometry and solid phase extraction (Wu et al., 2008; Wu et al., 2008). Wu et al. (2008) also investigated the occurrence of 18 commonly used pharmaceuticals runoff from septic systems in an agricultural area in the western Lake Erie basin (Wu et al., 2009). Chemical experiments were performed to test the adsorption and dictionary in soils with or without biosolids amended by Wu et al. (2009). Then the potential accumulation of PPCPs in soybean by biosolids land application was examined in greenhouse (Wu et al., 2010). Wu et al. also studied the transport of five pharmaceutical compounds in biosolids amended soil (Wu et al., 2010).

Research about microorganism has also published. Esseili et al. (2008) found a better way to characterize Escherichia coli communities associated with fecal pollution. Wu (2007) looked into the spatial relationship between sewage sludge application and *E. coli* along Lake Erie. The level of *E. coli* was analyzed from the two-year period water samples collected in ditches and Lake Erie near the sewage sludge treated fields. Spatial distribution of *E. coli* and sewage sludge applied fields were mapped, statistical analysis were applied to *E. coli* level, sewage sludge applied fields, and the local weather condition were considered in this study. The result showed that the water samples collected from the ditches and Lake Erie connected to treated fields contained higher level of *E. coli* (Wu, 2007). Occurrence of *mecA* in non-staphylococcal pathogens in surface waters was studied by Kassem et al. (Kassem et al., 2008). Wu et al. found in 2009 that five out of six antibiotics can be alive in biosolids and have the possibility to be brought to soils by biosolids land application (Wu et al., 2009).

Civil engineers are also cooperating to this project. Bhat and Kumar applied the Crystal Ball Software for predict concentration and risk levels for biosolids applications in the environmental field (Bhat and Kumar, 2008). It is helpful for environmental professionals to understanding the limitations of the results and to improve their decision making.

Monitoring sewage sludge application by remote sensing technology is another important portion in this project. The related studies are discussed in the next section.

2.3 Use of Remote Sensing to Study Crops, Soils and Biosolids Application

As described by Jensen, “Remote sensing is the art and science of obtaining information about an object without being in direct physical contact with the object. Remote sensing can be used to measure and monitor important biophysical characteristics and human activities on Earth” (Jensen, 2007). Vincent (1997) stated his theory of how remote sensing technology can sense the objects on the Earth without physical contact in his book *Fundamental of Geological and Environmental Remote Sensing*. He explained that the “electromagnetic waves emanating heat from and reflecting sunlight off the objects” can be detected by satellite sensors, thus the “characteristics of an object on the Earth surface” can be identified. The Wavelengths of electromagnetic waves are: X-ray μm), Ultra-violet ($10^{-2} - 0.4$ μm), Visible (0.4-0.7 μm), Reflective infrared (0.7-3 μm), Thermal infrared ($3 - 10^{2}$ μm) and Microwave ($10^{4} - 10^{6}$ μm). (Jensen, 2007)

The most appropriate satellite imagery to study biosolids application to farm fields is Landsat images, because of its spectral, spatial and temporal resolutions. For detecting the Class B sewage sludge applied on harvested agricultural fields, the crop types and the soil condition need to be determined from the images, but it does not require very high spatial and temporal resolution as precision agriculture. As shown in Figure 2-3 and Table 2.1, Landsat 5 and 7 are the best choice of data for this study.

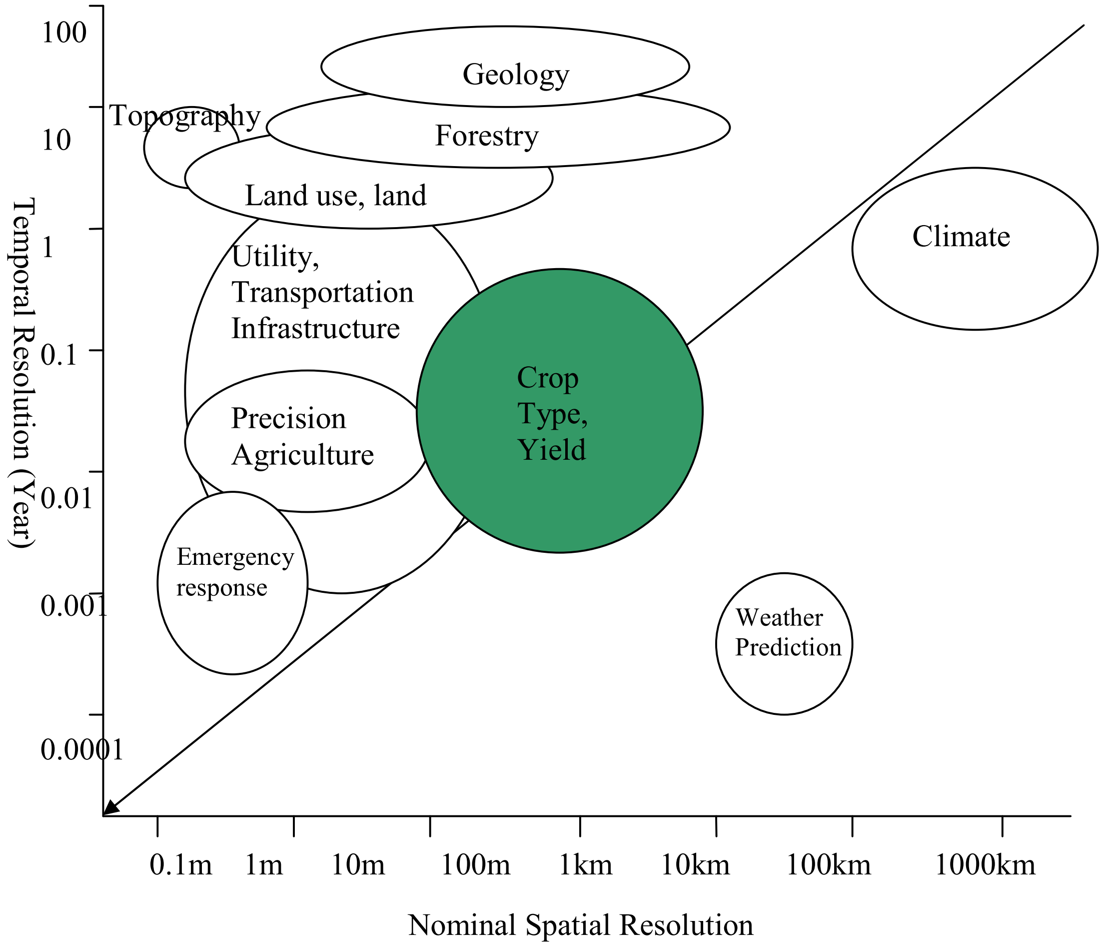


Figure 2-3: The nominal spatial and temporal resolutions for selected applications (Adapted from Jensen 2007, Remote sensing of the environment, color Plate1-1)

Table 2.1: Characteristics for Landsat 4, 5 and 7 sensor systems (Jensen, 2007)

Landsat 4 and 5 Thematic Mapper			Landsat 7 Enhanced Thematic Mapper+	
Band	Spectral Resolution (μ m)	Spatial resolution (m)	Spectral Resolution (μm)	Spatial resolution (m)
1	0.45-0.52	30*30	0.450-0.515	30*30
2	0.52-0.60	30*30	0.525-0.605	30*30
3	0.63-0.69	30*30	0.630-0.690	30*30
4	0.76-0.90	30*30	0.750-0.900	30*30
5	1.55-1.75	30*30	1.55-1.75	30*30
6	10.40-12.50	120*120	10.40-12.50	60*60
7	2.08-2.35	30*30	2.08-2.35	30*30
Revisit	16 days		16 days	
Launch	1982-7-16 (L4)	1984-3-1 (L5)	1999-4-15 (L7)	

Landsat 4 and 5 Thematic Mapper (TM) sensor systems were launched on July 16, 1982 and March 1, 1984, respectively. The choice of the bandswidths of Landsat TM is based on the research of “water penetration, discrimination of vegetation type and vigor, plant and soil moisture measurement, differentiation of clouds, snow and ice, and identification of hydrothermal alteration in certain rock types” (Jensen, 2007). It was improved from the Landsat 1, 2 and 3 MSS sensor systems (Jensen, 2007).

Landsat 7 was launched on April 15, 1999. It has higher spatial and spectral resolutions, which was improved from earlier Landsat TM Satellites. Landsat 7 provides data with the same “geometry, spatial resolution, calibration, coverage characteristics, and spectral characteristics” as previous Landsat satellites (Jensen, 2007). Unfortunately, a lot of data are missing since the ETM plus Scan Line Corrector (SLC) on Landsat 7 failed on May 31, 2003. Scientists have been trying to fix this problem, but they did not succeed (Jensen, 2007).

Sridhar et al. (2006) and Wang (2009) stated the chronological sequence of winter wheat, corn and soybean rotation and sewage sludge application in between. Generally, winter wheat was planted in October and harvested in June in the second year. Then sewage sludge may apply on harvested winter wheat fields from July to September. Corn grows from May to October in the third year, and then sewage sludge may be applied after corn was harvested. Soybean was grown from May to October in the fourth year. According to the sewage sludge application data, the sewage sludge was applied in Oregon, Ohio mostly in summer and fall. Sridhar et al. (2006) and Wang (2009) also mentioned that July to September can be a good time to observe sewage sludge application on harvested winter wheat fields by satellite images because corn and soybean were growing, and winter wheat has been harvested. On the July to September imagery, the agricultural fields with no vegetation on them are likely to be winter wheat harvested fields. And sewage sludge has to be applied on bare soil or stubble fields. Therefore, from July to September, the sewage sludge application fields are mostly winter wheat stubble fields (Wang, 2009).

There have been several recent projects that used remote sensing to detect the components and residues in soil as followed.

Dematte et al. (2003) showed that the electromagnetic reflectance from a soil sample can be used to detect the components in it. The reflectance tells us what kind of minerals are they, even their physical and chemical characteristics. Remote sensing is also effective in detecting the industrial residues in the soil. Aerial photos with high spatial resolution and satellite images with particular bandwidths were successful in identifying different elements in soil such as Nitrogen, Carbon, and Phosphorus (Varvel et al., 1999; Chen et al., 2000; Sridhar et al., 2009).

Boyd et al. (1979) reported that observation of the infrared spectra of sludge is a unique way to identify the “pertinacious polysaccharide” materials in sludge. Malley et al. (2002) predicted some of the nutrients and salt concentrations in manure by near-infrared spectroscopy. This research proved that the near-infrared spectroscopy can be used to monitor nutrients and salt concentrations. This study used “rapid nondestructive near-infrared spectroscopy” to analyze the components in hog manure. Soil spectral data were collected in the visible and near-infrared region. The soil spectral data were correlated with chemical lab data for the same soil samples. Multiple linear regressions were developed to predict for the unknown samples in the future.

McNulty (2005) concluded in her thesis that Class B sewage sludge did not have a "unique spectral signature". Other fertilizers and animal waste have similar spectral reflectance as Class B sewage sludge. She mentioned that it will be helpful for identifying Class B sewage sludge, if we know the "spectral signatures" of other types of fertilizers and animal waste.

It is encouraging that Sridhar et al. (2006) had a positive result for identifying sewage sludge applied fields. They discovered that the plants on sewage sludge applied fields have different spectral reflectance compare to those grown on control fields. And the spectral difference can be detected up to 65 days after sowing. When the metal concentration in the plants and soils were increasing, spectral reflectance was decreasing. They found the method to identify the sewage sludge surface application on winter wheat stubble fields. In the ratios of bands 7 and 5, bands 5 and 4, and bands 3 and 2, displayed in blue, green and red, respectively, were applied to Landsat TM images. In the ratio combination images, the winter wheat stubble fields with sewage sludge applied on the surface appeared gray, and the control fields appeared yellow.

Figure 2-4 shows winter wheat stubble fields after surface sewage sludge applied were darker by sight (Sridhar et al., 2006).

Figure 2-4: Sewage sludge surface application in Bowling Green, Ohio (top) and the difference of visual appearance afterwards (bottom). UT is untreated field and SAF is sludge applied field (Sridhar et al., 2006).

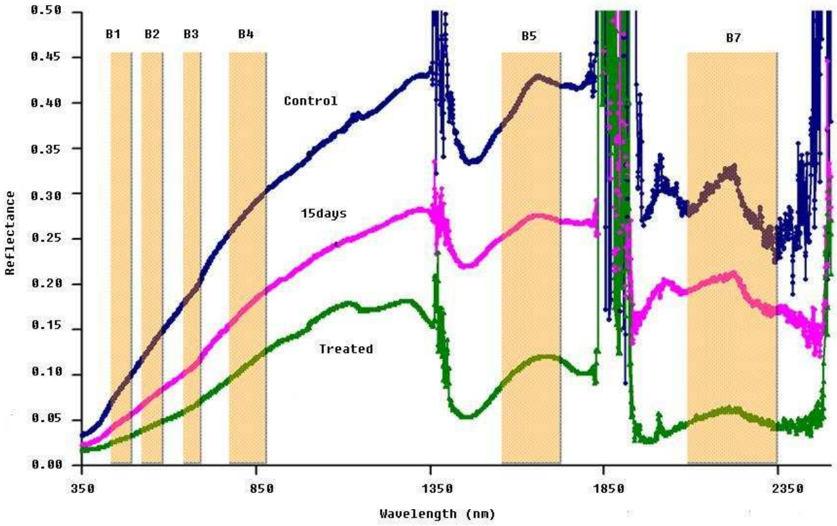


Figure 2-5: Field spectral reflectance of the sludge applied and untreated harvested winter wheat fields. Those data were collected by an ASD field spectroradiometer. Marked are the spectral ranges of Landsat bands 1 to 5 and 7. All the study sites were harvested winter wheat fields with senescent grass left as agricultural residue over the field. (Sridhar et al., 2006)

In Sridhar et al. (2006), soil samples were collected from three different kinds of fields: control field, treated field and 15 days after sewage sludge treated. Control field, shown as blue line, were the field that had not received sewage sludge. The treated fields, shown as green line, were the fields with sewage sludge treated on the surface. And "15 days" shown as pink line, were also treated fields, but the samples were collected 15 days after the field was treated by sludge. Figure 2-5 shows that spectral differences between sewage sludge treated fields and control fields exist, particularly in band 4, band 5 and band 7. Secondly, the spectral difference between sewage sludge applied fields and control fields became smaller in 15 days after sewage sludge application.

Wang (2009) extended the usage of spectral ratio combination of R(7,5), R(5,4) and R(3,2), displayed in blue, green and red, respectively, to monitor the application of sewage sludge and animal manure, such as chicken manure and cow manure. In the spectral ratio combination image, winter wheat control fields were yellow, sewage sludge treated fields were gray, fields with chicken manure were dark red, and fields with cow manure displayed as light brown.

Sridhar et al. (2009) mapped the total phosphorus concentration of biosolids amended surface soil using Landsat TM data. They stated that remote sensing images can be used to measure and map the spatial distribution of total phosphorus concentration on surface of the bare soil. Compared to single band models, the phosphorus spectral ratio model was more effective and accurate. This method can be easily applied to large area also. This phosphorus spectral ratio model is another useful way to identify sewage sludge application, because phosphorus concentration in surface soils, in some degree, reveals the amount of biosolids application. The limitation of the method is that it can be only applied to bare soil fields with lower soil moisture.


Figure 2-6: Sewage sludge injection application equipment and the way the field looks after sewage sludge injection

As mentioned in the introduction, the main objective of this study is to determine if Landsat TM data can be used to identify agricultural fields that have had sewage sludge applied through injection. Visually, injection application of sewage sludge is harder to detect than surface application (Figure 2-6). Sewage sludge was injected in those lacunas in about 10 to 12 inches deep, which shows in the picture on the right-hand side of Figure 3-7. But we still can see some sewage sludge on the surface of the soil, plus the physical, chemical and organically change of soil can still be detected. Therefore, for this research it will be assumed that the fields with injection sewage sludge application also have the spectral differences compare with control field, only not as obvious as surface application samples. The methodology used to address this issue is followed.

Chapter 3

Methodology

3.1 Study Site

The study area used in this thesis is Oregon, Ohio (41.65°N 83.46°W) a suburb of Toledo, Ohio, in Lucas County United States. According to the United States Census Bureau, the city has a total area of 98.7 km^2, of which, 76.1 km^2 is land and 22.6 km^2 it is water, mostly Lake Erie. As of the census of 2000, there were 19,355 inhabitants, 7,708 households, and 5,318 families residing in the City of Oregon. The population density was 254.4/km^2.

In glaciated western and northern Ohio, where the City of Oregon located, the bedrock surface is buried under glacial sediments, which can be several-hundred-feet thick (Figure 3-3). The land surface in this region was smoothed and complexly dissected by glaciations. The dissected bedrock surface is the result of erosion before, during and after glaciations. (Ohio Division of Geological Survey and Ohio Department of Natural Resources, 2003)

Figure 3-4 presents the 12 soil regions of Ohio. Oregon is at the northwest of Lucas County, in the soil region one, in pink color. Soil Region one is one of the portions of Ohio that was covered by a glacier during one or more glaciations. Soils in Regions one through eight tend to be deeper to bedrock than Regions nine through 12. Limestone, Dolomite and limy shales are the most common bedrocks in Soil Region one, and so the soils in Region 1 have relatively high lime content in the bottom.

Region one is also a part of the Erie-Huron Lake Plain, where the most common soils are lake and beach sediments and glacial till associated with glacial lakes. Region one is characterized by nearly level crop fields with drainage ditches and subsurface drains (Division of Soil and Water Conservation, Ohio Department of Natural Resources).

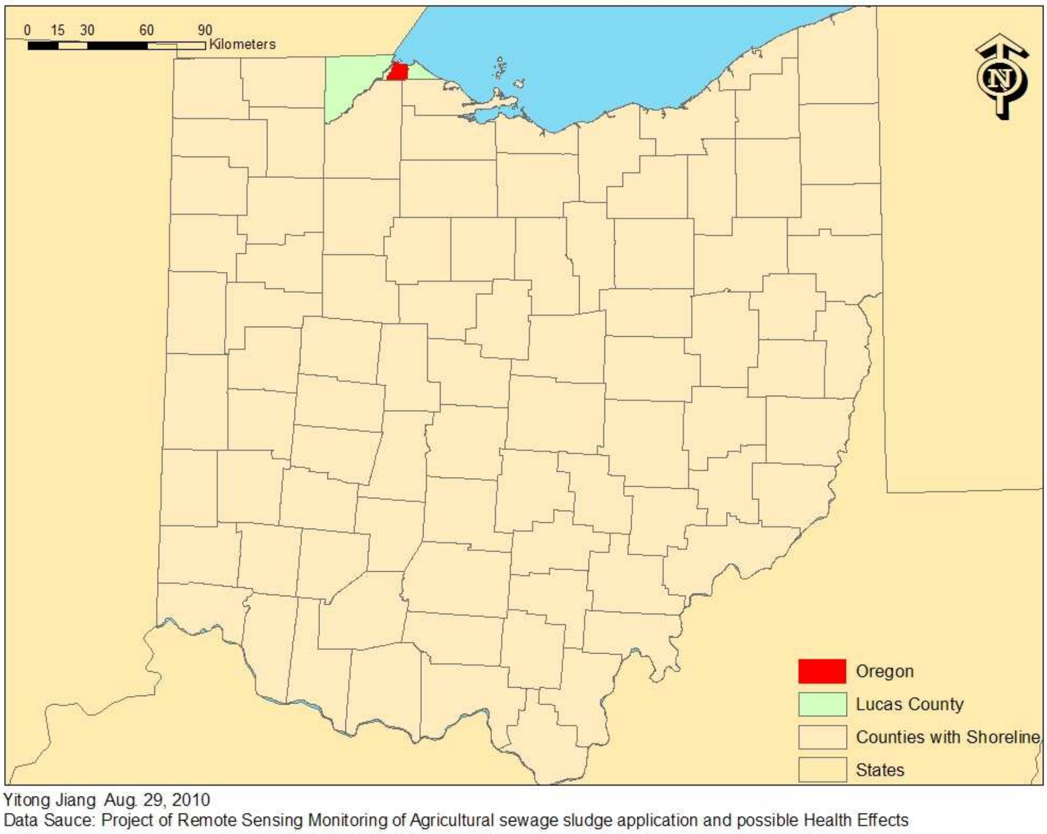


Figure 3-1: Location of the City of Oregon, Lucas County, Ohio.

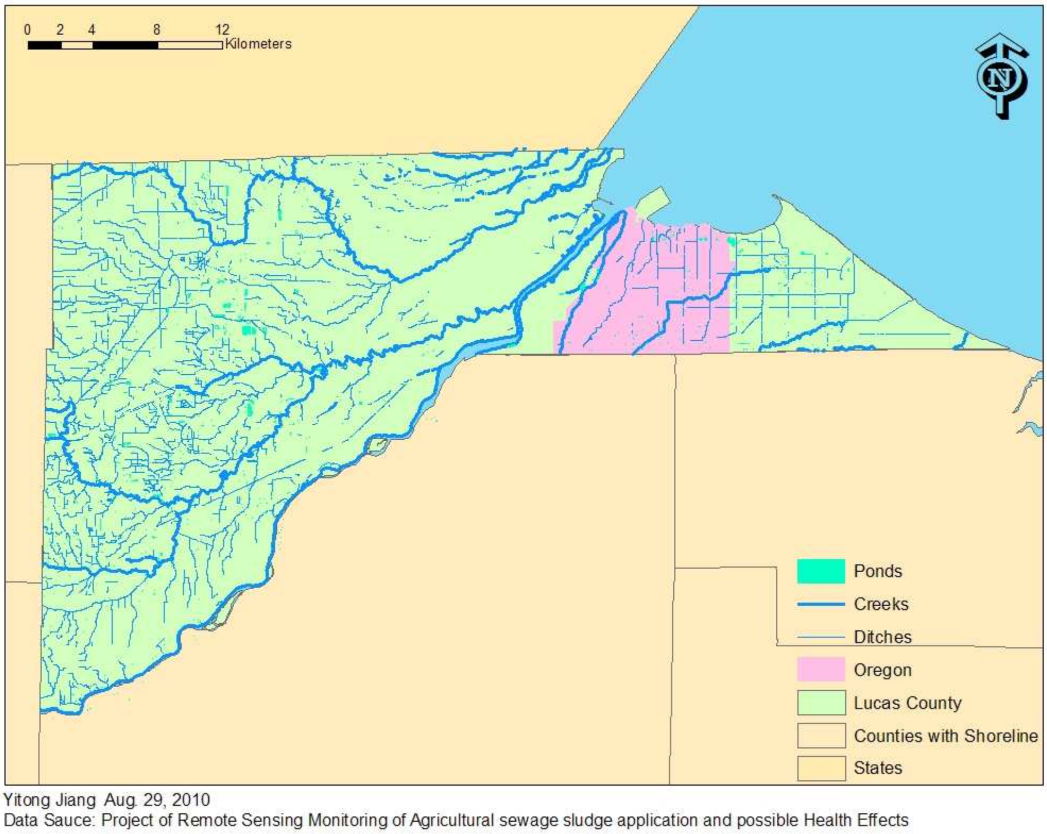


Figure 3-2: Surface-water resources in Lucas County, Ohio that drain into Lake Erie mostly through the Maumee River and creeks and ditches directly into Lake Erie. The pink area is Oregon, Ohio.

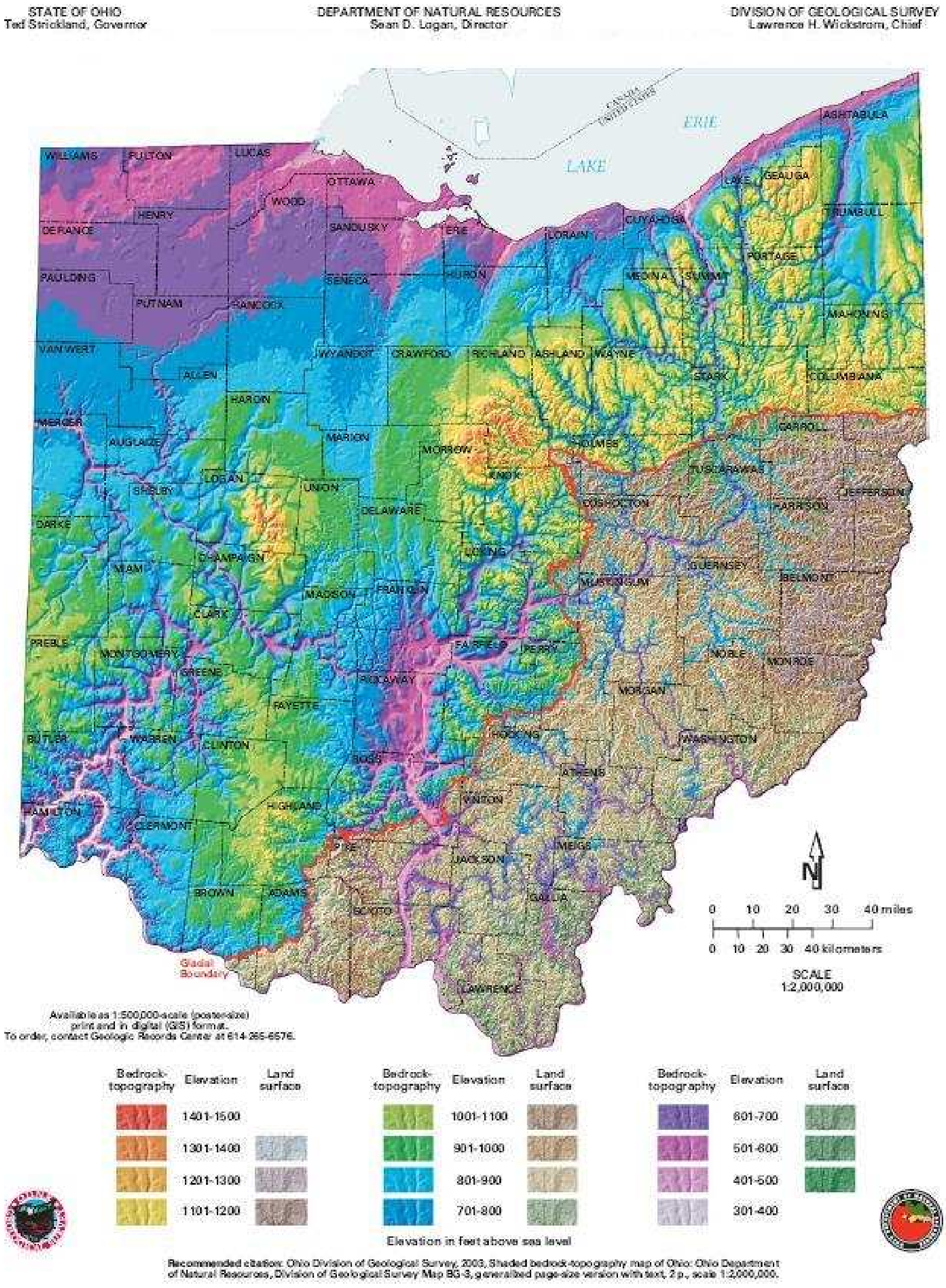


Figure 3-3: Shaded bedrock –topography map of Ohio (Source: Ohio Division of Geological Survey and Ohio Department of Natural Resources, 2003)

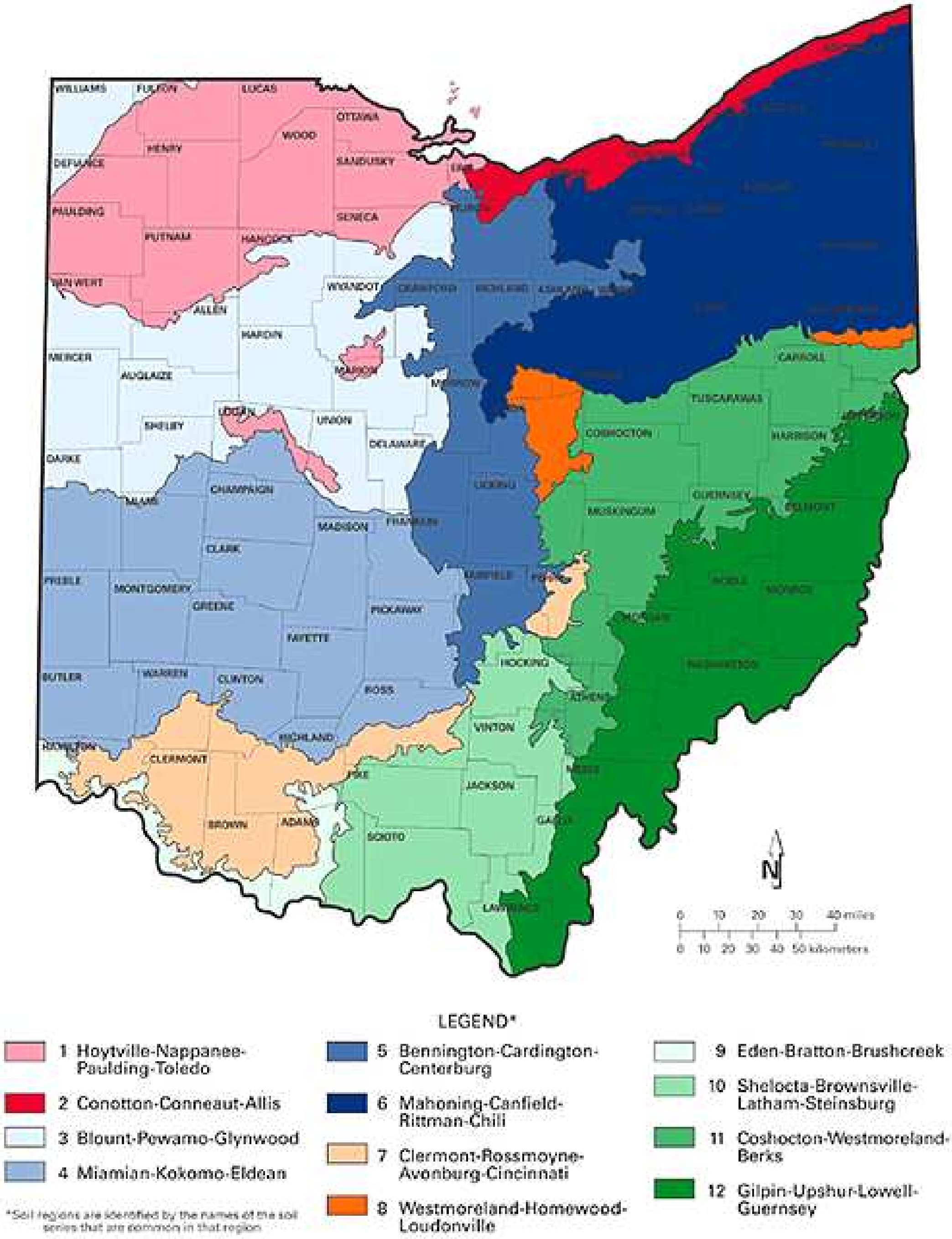


Figure 3-4: Soil regions of Ohio (Source: Division of Soil and Water Conservation, Ohio Department of Natural Resources, 1996)

3.2 Data Selection and Image Pre-processing

Based on the sewage sludge application data, the Landsat 7 and Landsat 5 images from 1999 to 2007 were chosen. The Landsat images available from Ohioview (http://www.ohioview.org/data-services/browse-landsat) are taken in 1985, 1994 and 1999 to Sep. 15 2007 (checked Feb. 7, 2010). The Scan Line Corrector (SLC) of the ETM+ instrument on Landsat 7 failed on May 31, 2003. Landsat 7 images from 1999 to 2002 and Landsat 5 images from 2003 to 2007 were used in this project. However, the finalized sewage sludge application data from Wastewater Treatment Plant, Oregon, Ohio, organized by April Ames and Xueying Chen shows that the sewage sludge application date is not accurate before 2003, so the Landsat 5 images from 2003 to 2007 were finally chosen for this thesis.

According to the location of the study area, the Landsat Images on Path 20, Row 31, which covers Northwest Ohio, Northeast Indiana, Southern Michigan, Southern Ontario and Western Lake Erie were chosen. USGS Glovis (http://glovis.usgs.gov/) has been double-checked for additional Landsat 5 images that were not found on Ohioview.

In order to do the cloud-free surface observation, cloud-cover percentage above Oregon, OH was checked, using Landsat Web-Based Visualization on Ohioview (www.ohioview.org) and USGS Glovis (http://glovis.usgs.gov/).

According to the sewage sludge application data and Sridhar et al. (2006), it was assumed that the fields with injection sewage sludge application within 15 days can still show some spectral differences to the fields that have not had sewage sludge applied. Table 3.1 shows the images that have the sewage sludge application within 3 to 46 days. Those images were processed with Erdas Imagine software, version 9.3.

Table 3.1: Image date, injection application fields and sewage sludge application finish date in Oregon, Ohio 2003-2007, arranged by the image-taken date

ID	Image Date	App fields	App Finish Dates	Number of days
1	10/6/2003	26I	9/26/2003	10
2	8/21/2004	25B	7/26/2004	26
3	9/6/2004	26J	7/22/2004	46
4	9/22/2004	25B	9/15/2004	7
5	4/18/2005	29C	4/15/2005	3
	4/18/2005	29B	4/14/2005	4
	4/18/2005	29A	4/12/2005	6
6	5/4/2005	29C	4/15/2005	19
	5/4/2005	29B	4/14/2005	20
	5/4/2005	29A	4/12/2005	22
7	9/9/2005	25G	8/27/2005	13
	9/9/2005	25F	8/26/2005	14
8	6/11/2007	35C	5/24/2007	18

3.2.1 Subset Images

Since this research is restricted to Oregon, OH, subseting the image into that area is needed. For the objects of study are agricultural fields, not all the urban area of Oregon, OH needs to be included in the subset images. So the Boundary of the City of Oregon (vector file) was not used to subset the images. Figure 3-5 shows the Path 20, Row 31 Landsat 5 image taken on April 18, 2005, bands 4, 3, 2, displayed as red, green and blue, respectively, projected with WGS_1984_UTM_Zone_17N and GCS_WGS_1984 as Geographic Coordinate System. The southern part of the image covers several counties in the State of Ohio. Figure 3-6 shows the subset image of April 18, 2005, which covers all the sewage sludge injection application fields in the study area through 2003 to 2007 and all the EPA permitted fields.

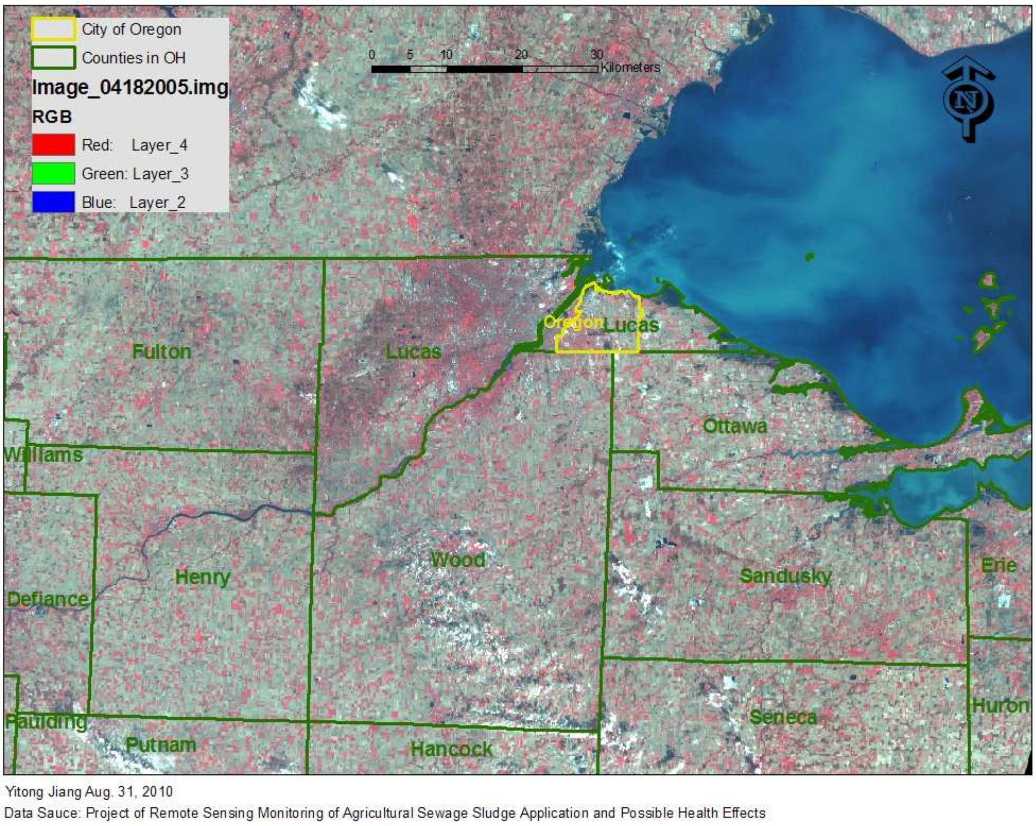


Figure 3-5: Subsection of a false color Landsat 5 Image taken on April 18, 2005 that covers several counties in northwest Ohio. Oregon is on the east side of Lucas County and the southern shore of Lake Erie.

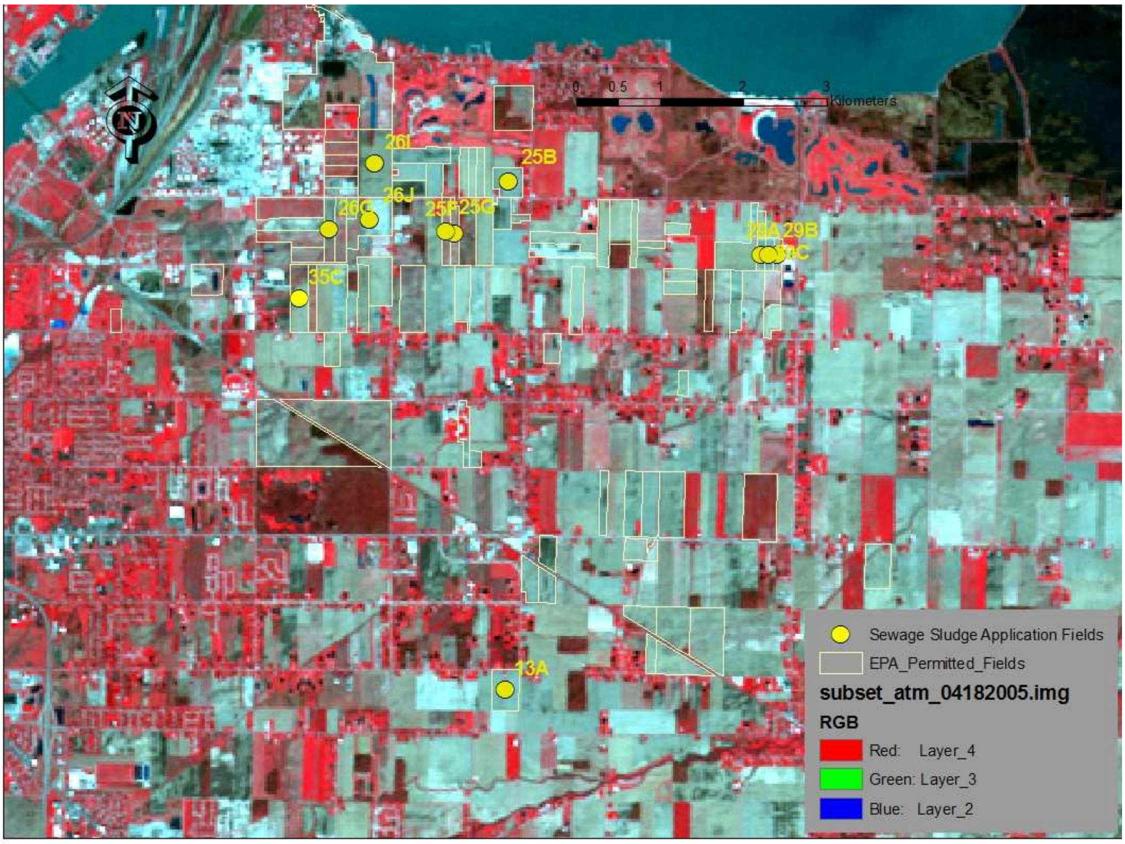


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Figure 3-6: Subset of a false color image for April 18, 2005 which includes part of the urban area and all of the agricultural area of Oregon, Ohio. Sewage sludge application fields are noted by yellow circles.

3.2.2 Atmospheric Correction

Atmospheric correction is needed to reduce the atmospheric effects and increase the study accuracy, when several satellite images are used in a project. Atmospheric correction was applied on band 1 to band 7 of the subset images. It was possible to assume that those images were taken under the same weather conditions. To do this, the histogram, which displays the range of pixel values and the number of pixels for different values, for each band of each image was checked. The minimum pixel values vary from band to band, and it gets lower as the wavelength center increases (Vincent et al., 2004). The minimum pixel value from each spectral band was subtracted, which makes the minimum pixel value of each band start from 0. The results of the atmospheric correction are shown in Table 3.2.

Table 3.2: The atmospheric correction for all chosen images 2003-2007

Bands	Image Date	Minimum		Image Date	Minimum		Image Date	Minimum	
	10/6/2003	before	after	8/21/2004	before	after	9/6/2004	before	after
1		37	0		42	0		47	0
2		11	0		14	0		17	0
3		5	0		2	0		10	0
4		0	0		0	0		0	0
5		0	0		0	0		0	0
6		67	0		82	0		104	0
7		0	0		0	0		0	0
	9/22/2004	before	after	4/18/2005	before	after	5/4/2005	before	after
1		41	0		66	0		55	0
2		13	0		22	0		18	0
3		5	0		17	0		12	0
4		0	0		7	0		0	0
5		0	0		0	0		0	0
6		82	0		80	0		72	0
7		0	0		0	0		7	0
	9/9/2005	before	after	6/11/2007	before	after			
1		36	0		58	0			
2		15	0		23	0			
3		8	0		13	0			
4		1	0		6	0			
5		1	0		1	0			
6		97	0		94	0			
7		1	0		1	0			

3.3 Examination of Spectral Characteristics

For each field listed in Table 3.1, pixel values were extracted and the average pixel value was calculated. ERDAS Imagine remote sensing software was used to convert the pixels using the ASCII function to extract the pixel values for each field. The average pixel value for band 1 to band 5 and band 7 were plotted. We do not have a yearly crop classification record until 2005. Therefore, for 2003 and 2004, there are chances that errors may occur when pick control field in each image. Based on the crop classification record for 2005, all four control fields were taken in 2005: one from April 18, 2005 image, one from May 4, 2005 image, and two from September 9, 2005 image. The pixel values for control fields were extracted, and the average pixel value for each control field was calculated. All the tables of pixel values, average pixel values and standard deviation for each treated field and control field are listed in the Appendix and are plotted in the Chapter 4. Detectable spectral differences between the study fields and control fields were expected.

3.4 Spectral Ratio Image

Spectral ratio imaging is beneficial because it reduces variations from environmental factors, such as "topographical slope and aspect, variations in solar illumination and elevation" (Vincent, 1997). The spectral ratio combination of R(3,2), R(7,5) and R(5,4) was applied, where R(3,2) is band 3 divided by band 2, R(7,5) is band 7 divided by band 5, and R(5,4) is band 5 divided by band 4. The ratio combination displayed in red, blue and green, respectively, was processed to images taken on April 18, 2005, May 4, 2005, September 9, 2005 and October 6, 2003, to differentiate the fields with sewage sludge injected application from those without sewage sludge application. Because of the atmospheric correction that was performed, the minimum value for each band could be 0. To avoid 0 in denominator, 0.1 was added to the denominator of each ratio. In the research Sridhar et al. (2006) and Wang (2009) did before, the control fields appeared yellow, and treated fields with sewage sludge applied on surface appeared gray. In this research, it is expected that control fields appear yellow, while treated fields with sewage sludge injected appear gray. The possibility of using this technique to monitor fields with sewage sludge injected over a large area will be tested.

Chapter 4

Results

4.1 Spectral Characteristics of Sewage Sludge Injected Application Fields versus Control Fields

The following are the Landsat 5 images and the fields that had sewage sludge injected on them. A total of eight images were chosen: one in 2003, three in 2004, three in 2005 and one in 2007 (Table 3.1). The study fields in these images had sewage sludge injected within 3 to 46 days before the images were taken. Sridhar et al. (2006) indicated that the spectral difference for the fields with sewage sludge surface application could be detected up to 30 days past application. Since the spectral difference for injection application is harder to detect, it was assumed that the fields with injection application could be detected in a Landsat image within 15 days of application. In Table 4.1, the study fields were arranged based on the number of days after sewage sludge application. Figures 4-1 to 4.7 show the eight images with the sewage sludge application fields marked on it.

Table 4.1: Selected Lansat 5 images and sewage sludge applied fields. The Landsat 5 images were taken 3 to 46 days after sewage sludge was injected into designated fields arranged by date.

ID	Number of days after application	Image Date	App fields	App Finish Dates
1	3	4/18/2005	29C	4/15/2005
2	4	4/18/2005	29B	4/14/2005
3	6	4/18/2005	29A	4/12/2005
4	7	9/22/2004	25B	9/15/2004
5	10	10/6/2003	26I	9/26/2003
6	13	9/9/2005	25G	8/27/2005
7	14	9/9/2005	25F	8/26/2005
8	18	6/11/2007	35C	5/24/2007
9	19	5/4/2005	29C	4/15/2005
10	20	5/4/2005	29B	4/14/2005
11	22	5/4/2005	29A	4/12/2005
12	26	8/21/2004	25B	7/26/2004
13	46	9/6/2004	26J	7/22/2004

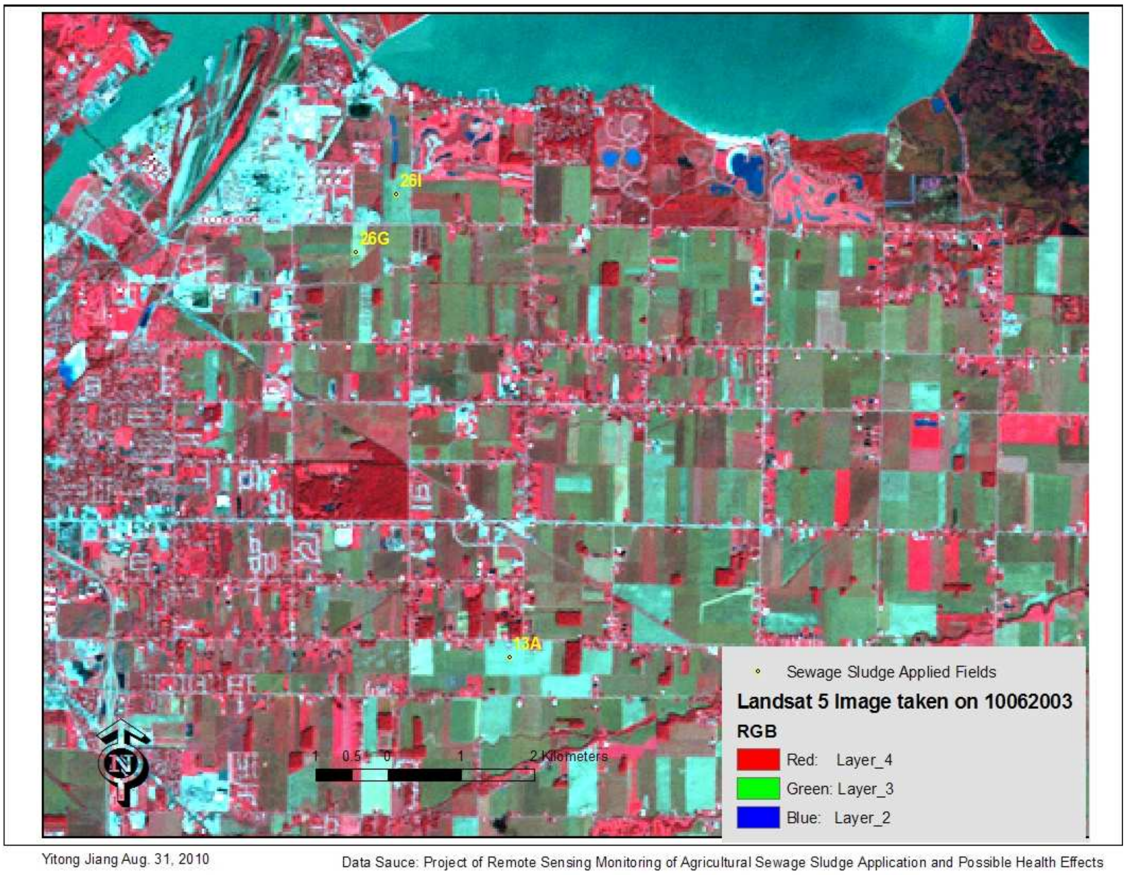

Figure 4-1: False color Landsat 5 image taken on October 6, 2003 with sewage sludge applied on 26I. Field 26I had received sewage sludge injection 10 days before the image was taken.

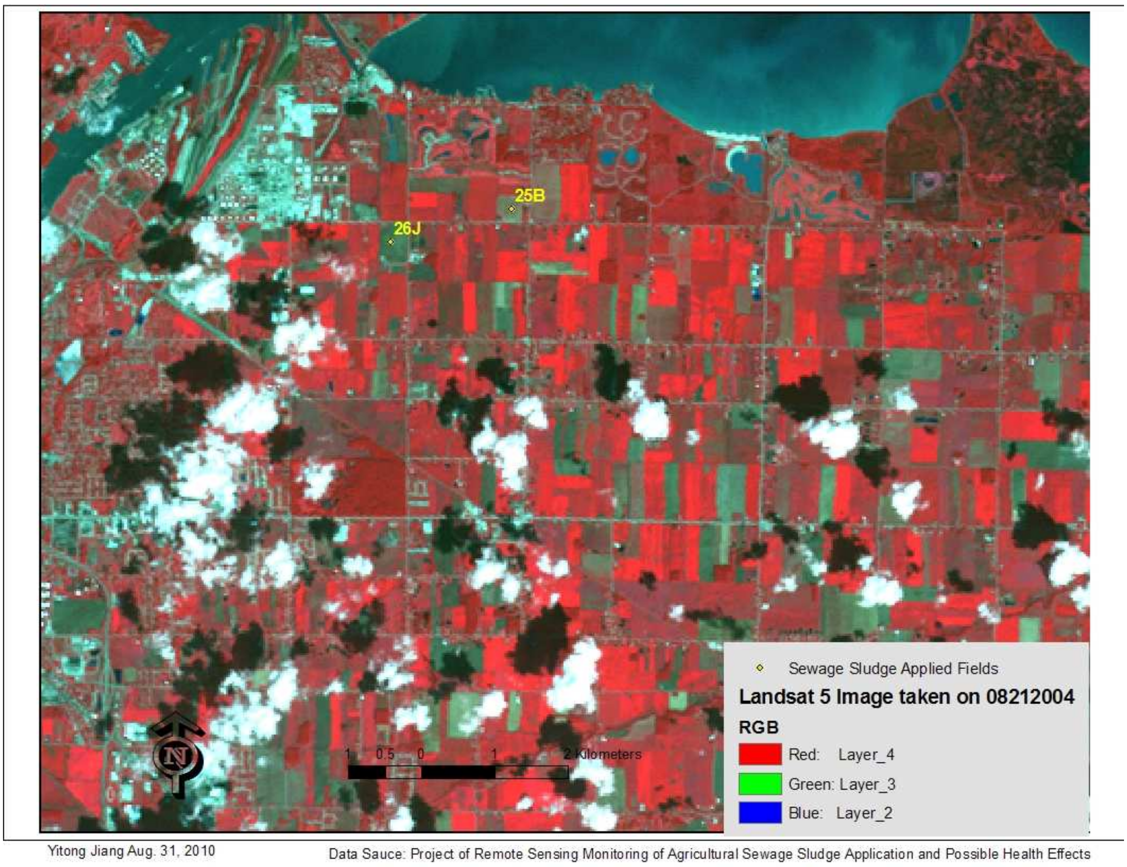

Figure 4-2: False color Landsat 5 image taken on August 21, 2004 with sewage sludge applied on 25B. Field 25B had received sewage sludge injection 26 days before the image was taken.

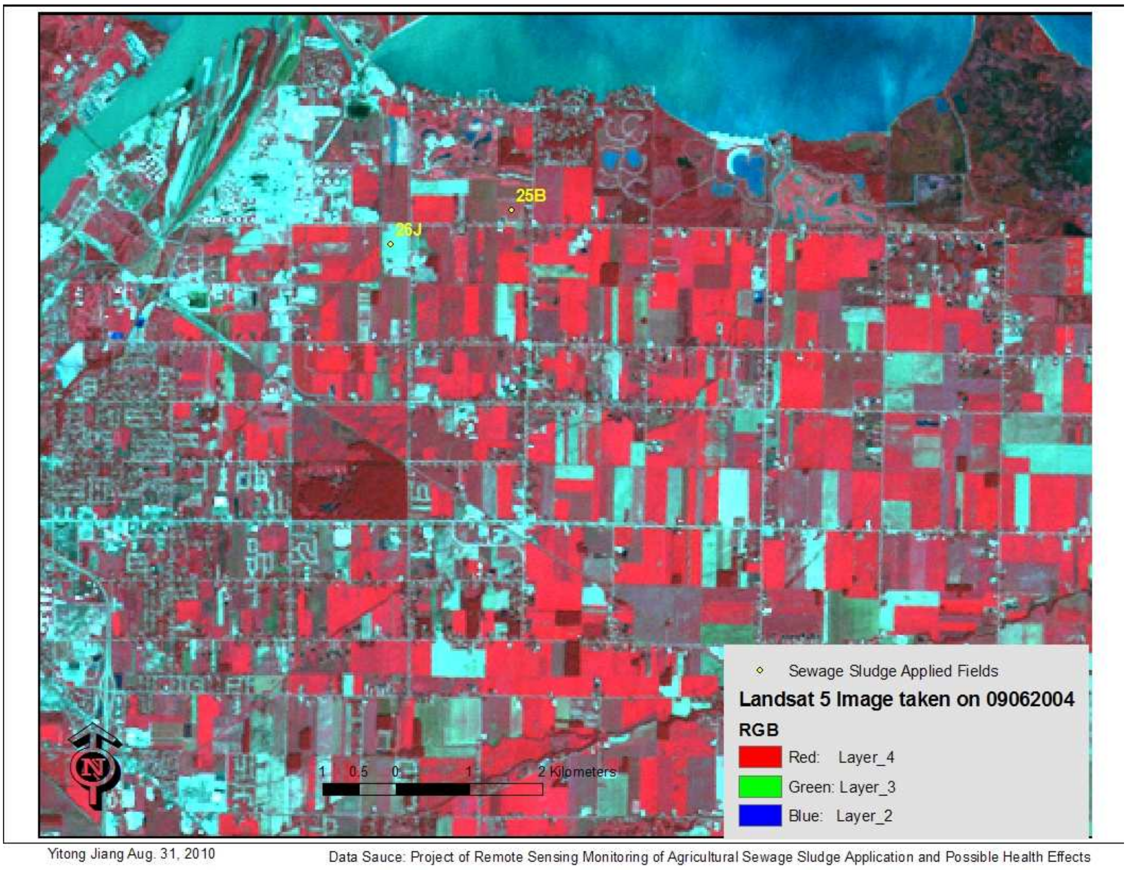

Figure 4-3: False color Landsat 5 image taken on September 6, 2004 with sewage sludge applied on 26J. Field 26J had received sewage sludge injection 46 days before the image was taken.

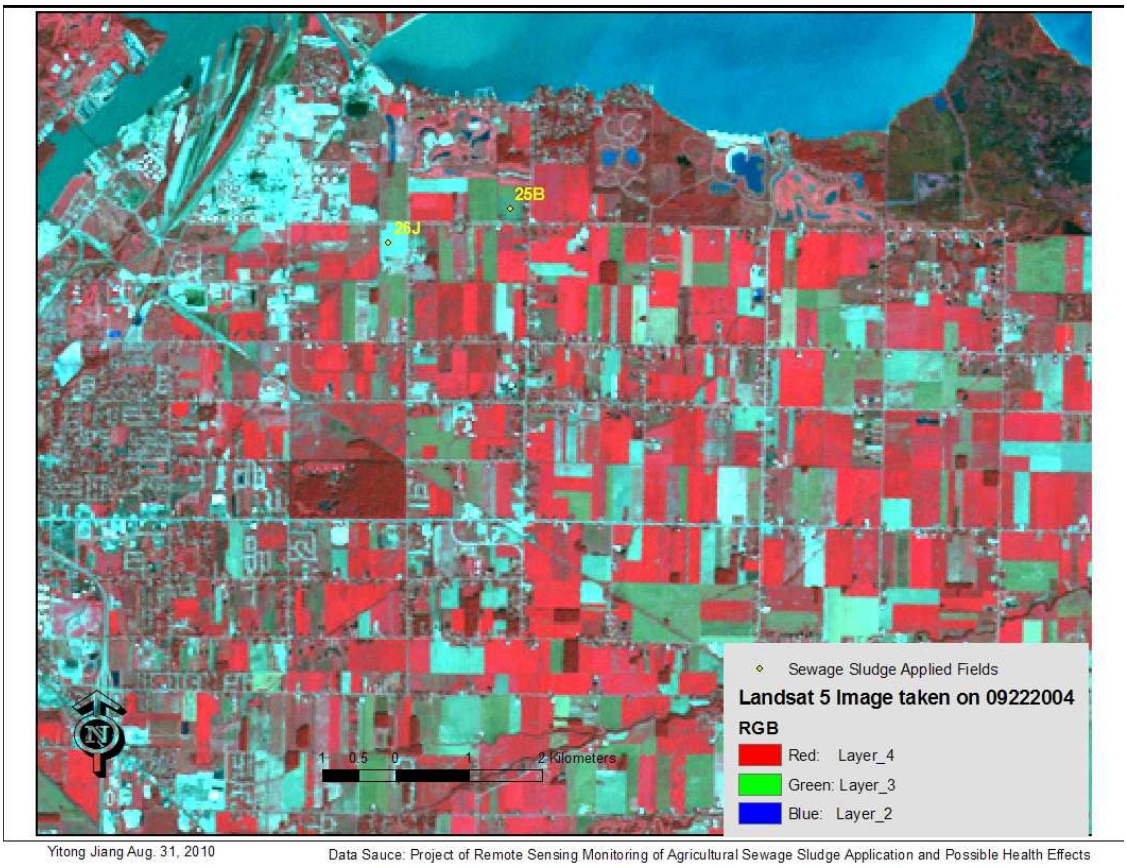

Figure 4-4: False color Landsat 5 image taken on September 22, 2004 with sewage sludge applied on 25B. Field 25B had received sewage sludge injection 7 days before the image was taken.

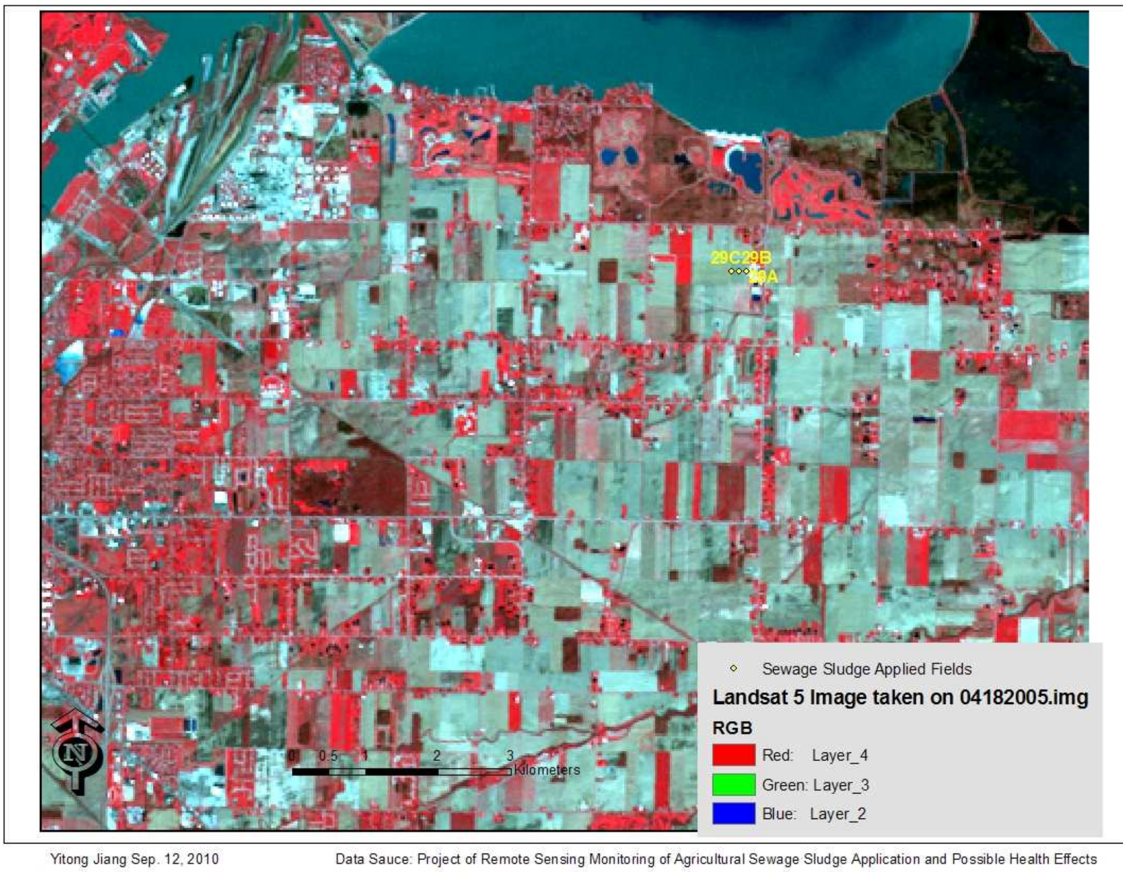

Figure 4-5: False color Landsat 5 image taken on April 18, 2005 with sewage sludge applied on 29A, 29B and 29C. Fields 29A, 29B and 29C had received sewage sludge injection 6, 4, and 3 days, respectively, before the image was taken.

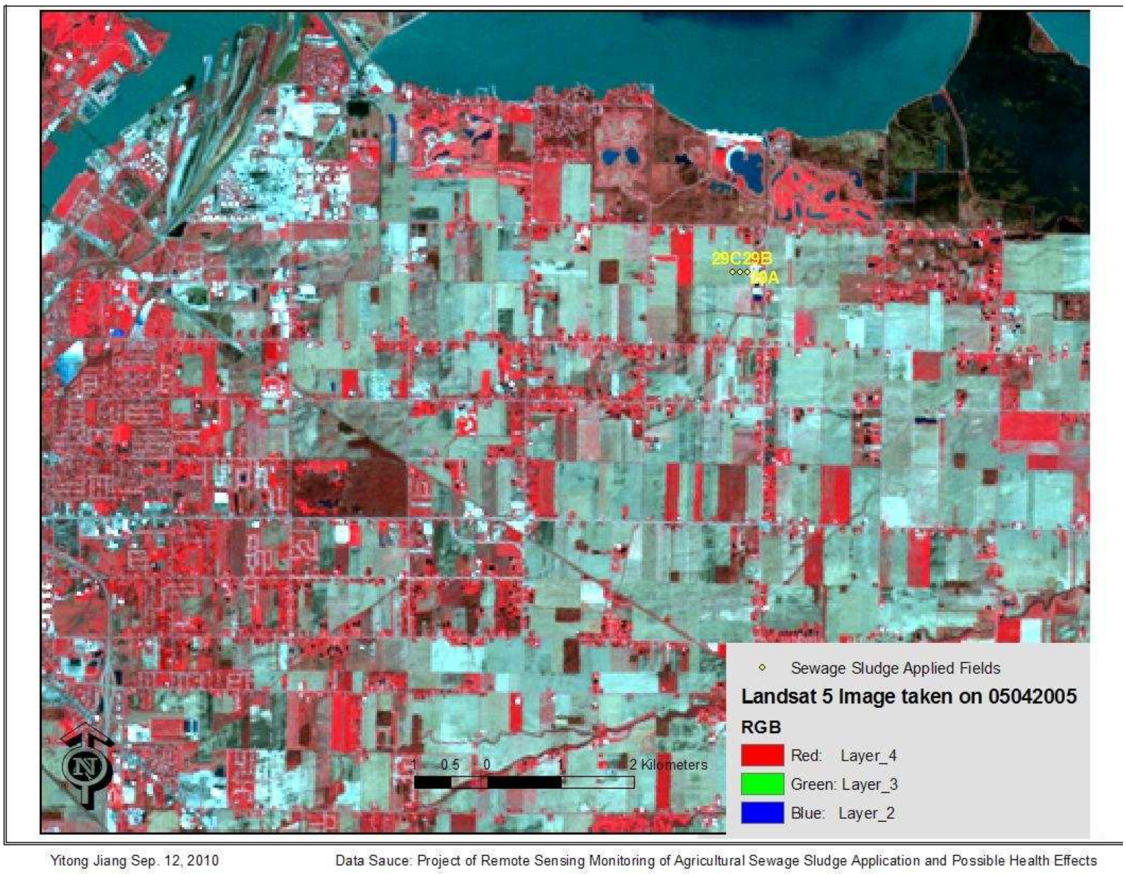

Figure 4-6: False color Landsat 5 image taken on May 4, 2005 with sewage sludge applied on 29A, 29B and 29C. Fields 29A, 29B and 29C had received sewage sludge injection 22, 20, and 19 days, respectively, before the image was taken.

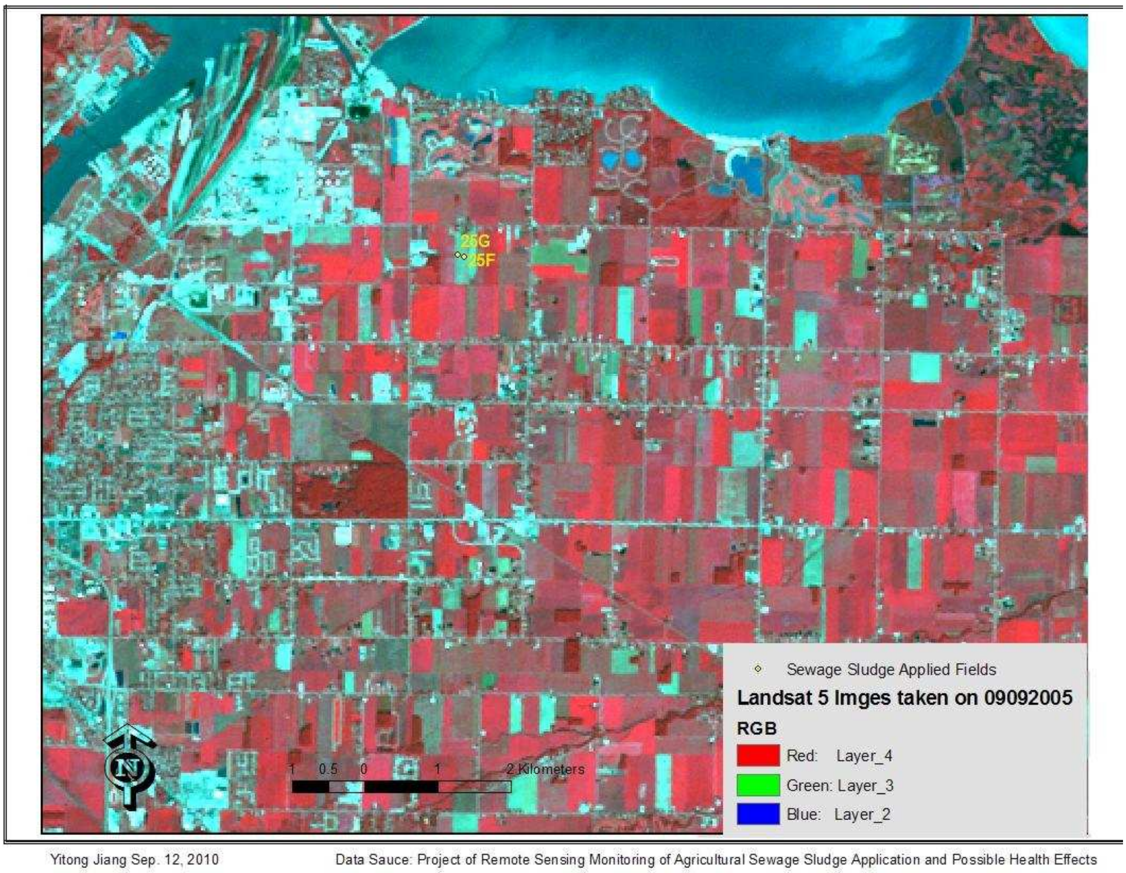

Figure 4-7: False color Landsat 5 image taken on September 9, 2005 with sewage sludge applied on 25G and 25F. Fields 25G and 25F had received sewage sludge injection 13 and 14 days before the image was taken.

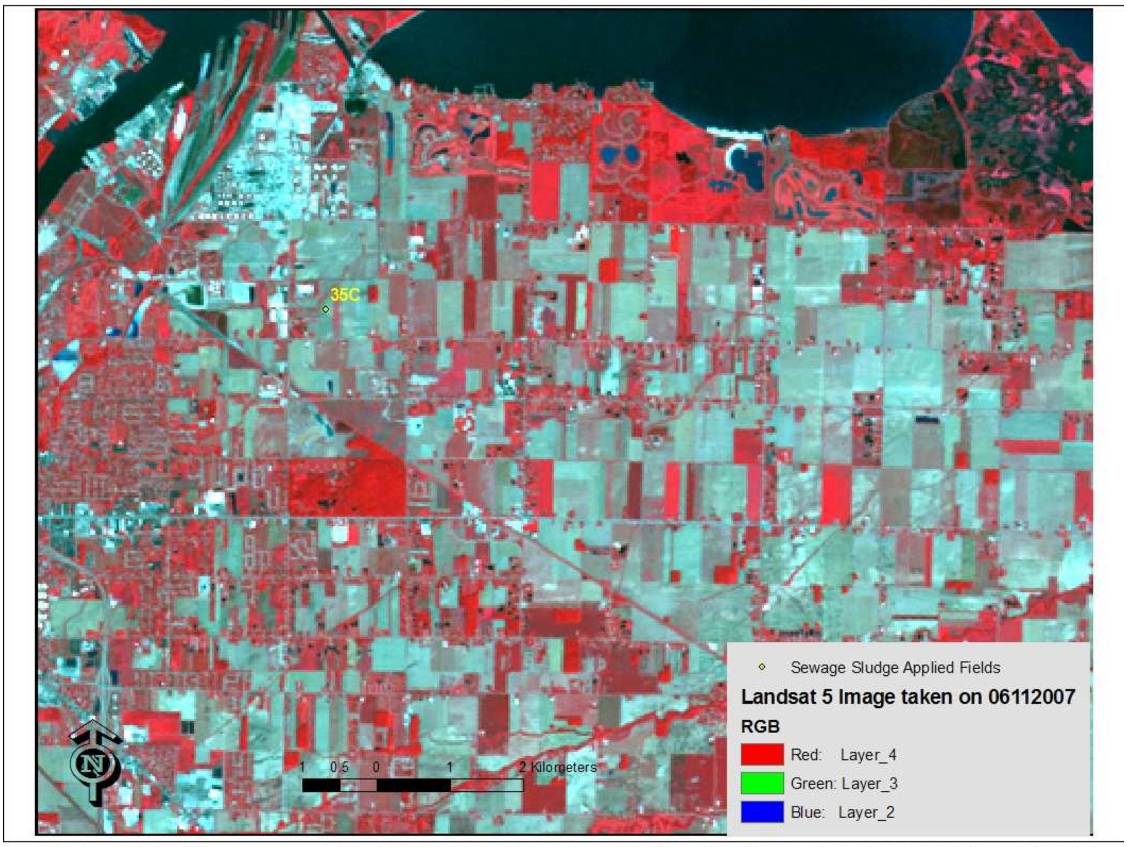

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Figure 4-8: False color Landsat 5 image taken on June 11, 2007 with sewage sludge applied on 35C. Field 35C had received sewage sludge injection 18 days before the image was taken.

The pixel values of the study fields were extracted from the images using ASCII function on Erdas Imagine software. The average pixel value and standard deviation of band 1 to band 5 and band 7 for each field with sewage sludge injected was calculated, and are listed in Table 4.2. Not all the fields with sewage sludge application shown in Figure 4-1 to Figure 4-8 were selected as the study fields in this research.

Table 4.2: The average pixel value and standard deviation of each treated field

Number of days	Image Date	Fields	B1	B2	B3	B4	B5	B7
3	4/18/2005	29C	31.80±1.63	26.55±0.51	45.90±0.85	57.80±0.95	127.45±2.84	75.10±1.21
4	4/18/2005	29B	32.80±1.97	27.40±0.77	46.90±0.96	59.40±1.07	128.57±1.65	76.20±1.69
6	4/18/2005	29A	33.42±2.05	28.48±1.23	48.24±1.89	61.30±2.14	132.55±3.78	77.91±2.11
7	9/22/2004	25B	26.68±1.37	18.23±0.62	32.58±0.81	48.50±1.50	80.58±1.99	39.20±1.11
10	10/6/2003	26I	30.78±1.53	20.67±0.91	34.93±1.35	42.94±1.46	87.99±3.42	46.42±1.76
13	9/9/2005	25G	42.53±1.23	23.35±0.86	38.12±0.70	59.06±2.25	104.41±2.83	54.82±1.91
14	9/9/2005	25F	43.44±0.88	23.89±0.60	37.89±0.60	61.00±1.32	101.22±2.99	52.44±2.01
18	6/11/2007	35C	46.08±1.54	28.19±1.74	49.00±3.13	63.00±3.87	132.33±10.71	78.39±5.33
19	5/4/2005	29C	42.80±1.36	30.55±0.51	50.90±0.85	64.80±0.95	127.45±2.84	75.10±1.21
20	5/4/2005	29B	43.80±1.97	31.40±0.77	51.90±0.96	66.40±1.07	128.57±1.65	76.20±1.69
22	5/4/2005	29A	44.42±2.05	32.48±1.23	53.24±1.89	68.30±2.14	132.55±3.78	77.91±2.11
26	8/21/2004	25B	32.44±2.16	21.38±0.89	38.06±2.32	73.25±2.96	98.31±3.88	39.25±2.44
30	9/6/2004	26J	45.10±1.84	28.58±1.18	46.86±2.01	59.35±2.08	102.39±4.19	58.67±2.64

As discussed in Chapter 3, the average spectral pixel values for control fields were calculated as followed. Control fields were chosen from Landsat TM Images taken on April 18, 2005, May 4, 2005 and September 9, 2005 (Figure 4-9). The pixel values were extracted from each of the control fields, and the average pixel values for the four control fields were used as the pixel value of control field to compare with the treated fields.

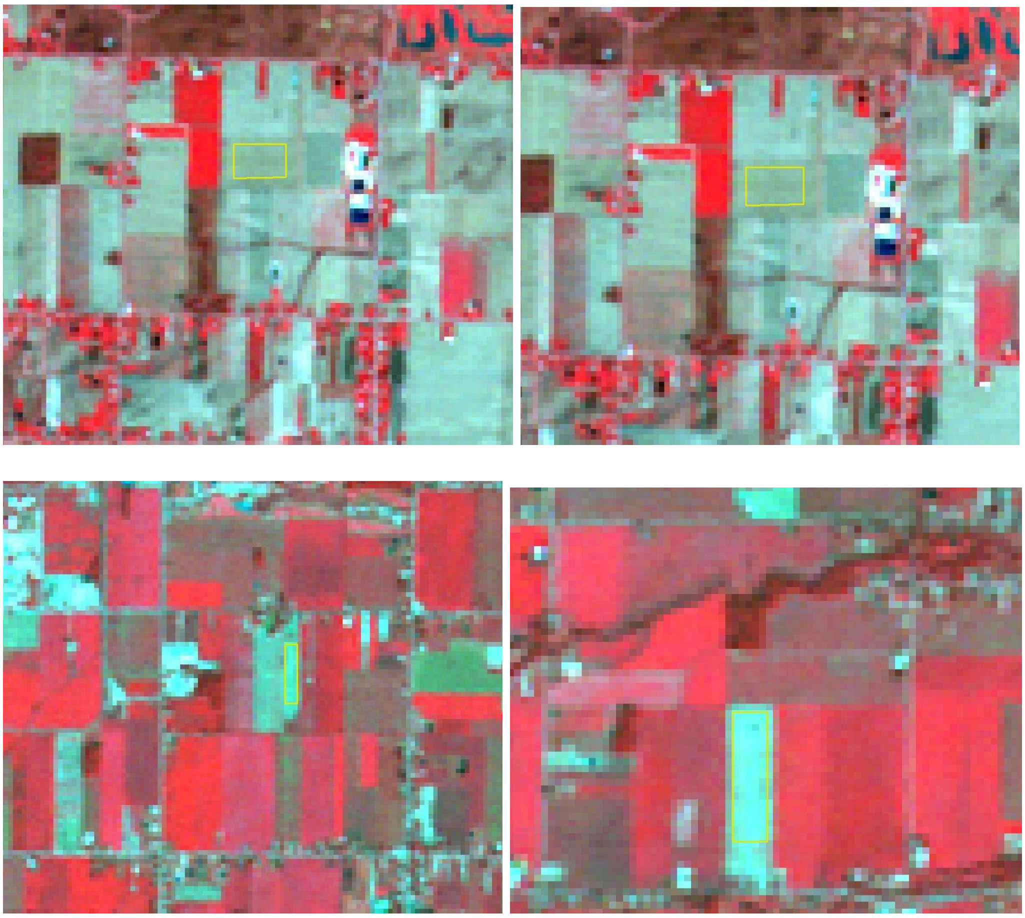


Figure 4-9: Four Landsat TM images taken on April 18, 2005 (upper left), May 4, 2005 (upper right), September 9, 2005 (lower left) and September 9, 2005 (lower right) showing control fields in yellow squares.

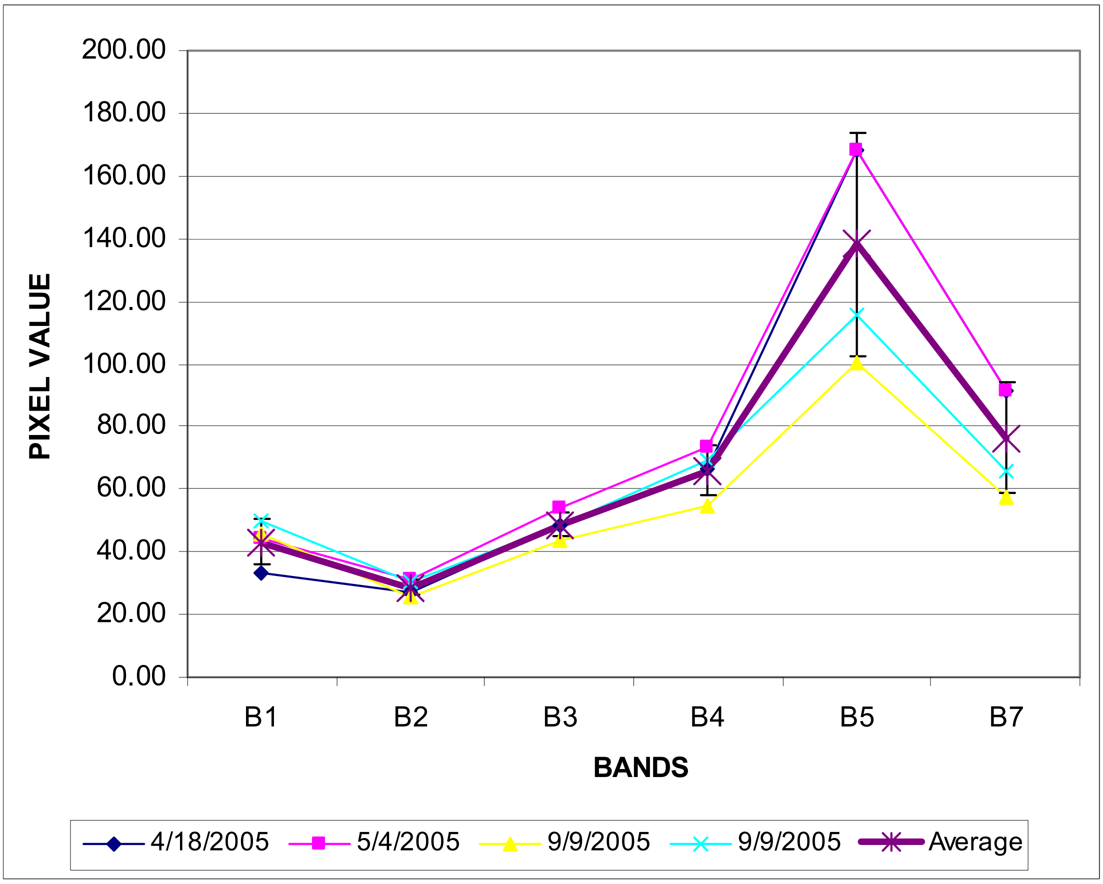


Figure 4-10: The pixel value for the four control fields taken from Landsat TM images from April 18, 2005, May 4, 2005 and September 9, 2005, respectively, and the average of the four. Y error bar is the standard deviation of the pixel value for each field and the average for four fields.

The large standard deviation of the average pixel value of the four control fields affected the accuracy. A plot of the pixel values and standard deviations of the treated fields and control fields showed that from 3 days to 14 days after sewage sludge injection application, the spectral difference between sewage sludge applied fields and control fields are all detectable, especially for band 4, band5 and band7. The spectral difference between study and control fields should become smaller and smaller from 3 to 14 days after sewage sludge application. However, the reasonable change of the spectra was not found in this case. This might have something to do with the selection of control fields. Not only the sewage sludge application, but also the seasons, weather conditions and crop types could affect soil spectral characteristics.

Therefore, the data was divided into two groups. Six out of the eight images were taken in August, September, and October. The study fields in the images which were taken in April, May and June were compared with control fields in the April and May images. And the study fields in the images which were taken in August, September and October were compared with the control fields in the September image. Table 4.3 shows the pixel values, average pixel values and standard deviations for two groups of control fields. The spectral profile of treated and control fields were plotted in Figure 4-11 to Figure 4-14.

Table 4.3: Pixel values, average pixel values and standard deviations for two groups of control fields

Group 1	B1	B2	B3	B4	B5	B7
2005-4-18	33.00	26.85	48.68	66.61	168.43	91.44
2005-5-4	44.00	30.85	53.68	73.61	168.43	91.44
Average	38.50	28.85	51.18	70.11	168.43	91.44
Standard Deviation	7.78	2.83	3.54	4.95	0.00	0.00
Group 2	B1	B2	B3	B4	B5	B7
2005-9-9	45.67	25.87	43.87	54.47	100.27	57.13
2005-9-9	49.96	30.58	48.67	69.40	115.38	65.56
Average	47.81	28.23	46.27	61.93	107.82	61.35
Standard Deviation	3.03	3.34	3.39	10.56	10.68	5.96

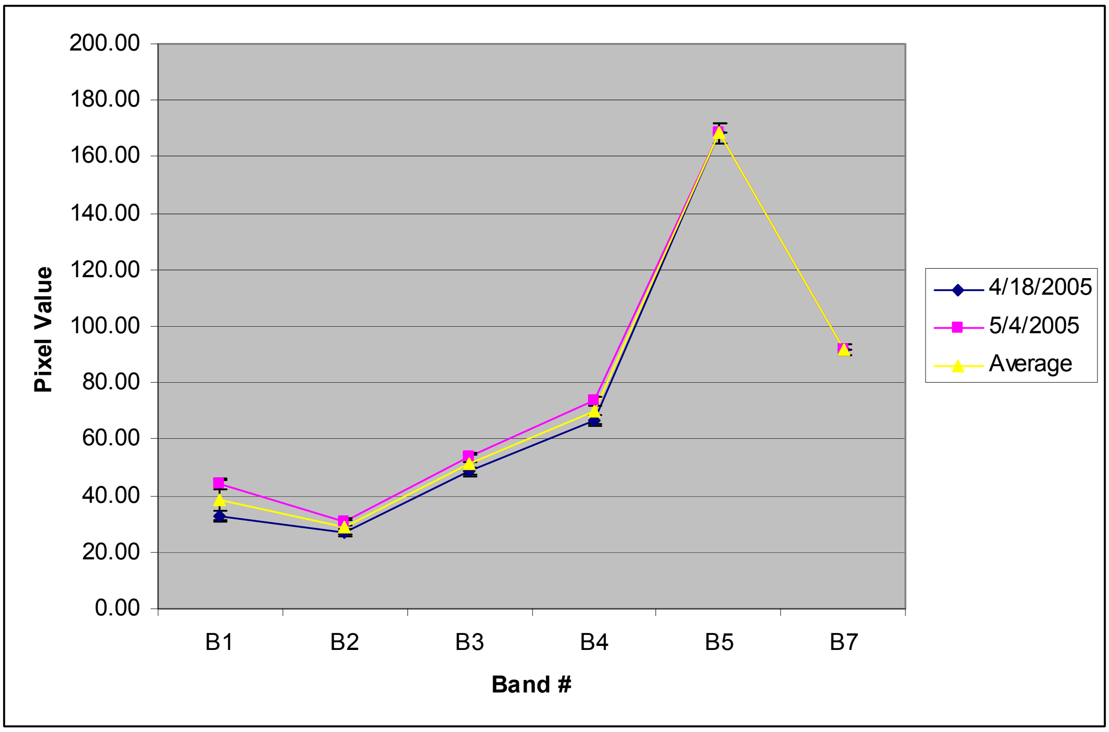


Figure 4-11: Group 1 spectral profiles and their average for two sample control fields in Landsat TM images taken on April 18, 2005 and May 4, 2005, respectively. The pixel value for band 1 to band 5 and band 7 were plotted. The standard deviations were plotted as the Y error bars.

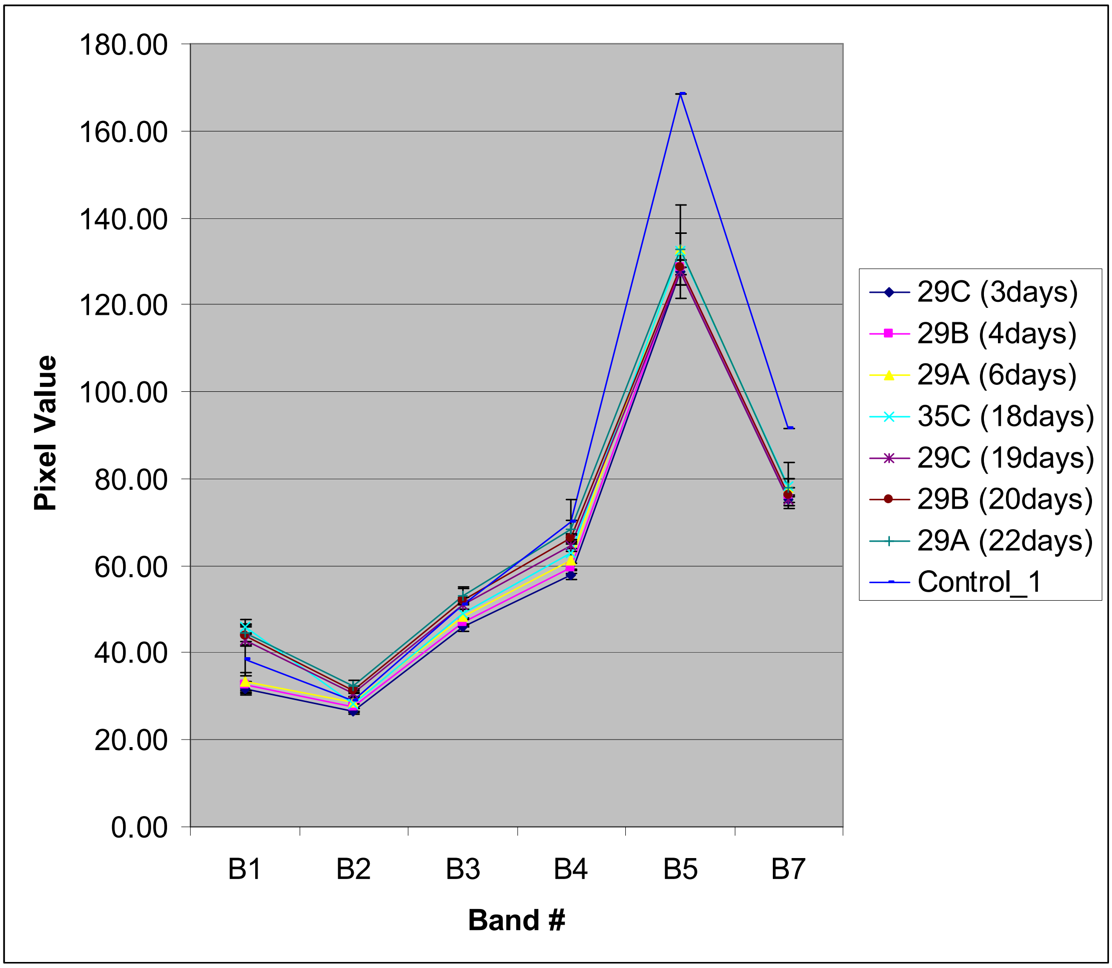


Figure 4-12: Group 1 spectral profiles for seven sample study fields and the average of Group 1 control fields. The pixel value for bands 1 to 5 and band 7 were plotted. The standard deviations were plotted as the Y error bars. The number of days after sewage sludge application for each field was shown in the legend.

In Figure 4-11, the control fields, red and blue lines, are actually one control field from two images. So they have very similar spectral characteristics. The standard deviations of the average are small. In band 5 and band 7, they even have the same pixel value. Figure 4-12 displays a large difference between observations of the treated and control fields as presented by band 5 and band 7. But the spectral change of the study fields was not as obvious as expect in band 5 and band 7. Observing the pixel values in band 5 and band 7, to identify the study fields out of the control fields was easy. 22 days later, the spectral difference between the study field 29A and average of control fields is still 35.88 in band 5, and 13.53 in band 7. The standard deviation of 35C in June 11, 2007 image is 10.71 in band 5. Even with the relatively large standard deviation, 35C still has 25.39 spectral difference from the control fields. Similar to band 5, 35C has a relatively big standard deviation in band 7 too. But with the 5.33 standard deviation, 35C still has 7.72 spectral difference from the control fields.

The pixel values in band 4 does not show much difference between study and control fields, but it shows clearly the spectral change of the study fields from 3 days to 22 days after sewage sludge application. The spectral pixel values of the study fields in band 4 are: 57.80 (29C, three days after application), 59.40 (29B, four days after application), 61.30 (29A, six days after application), 63.00 (35C, 18 days after application), 64.80 (29C, 19 days after application), 66.40(29B, 20 days after application) and 68.30 (29A, 22 days after application). The average spectral pixel value of control fields is 70.11. The standard deviation of control field is 4.95. The pixel value of the study fields 29C (19 days after application), 29B (20 days after application) and 29A (22 days after application) are in the range of the standard deviation of control fields. Therefore, it was hard to separate the study fields from the control fields by band 4 only 18 days after sewage sludge injection.

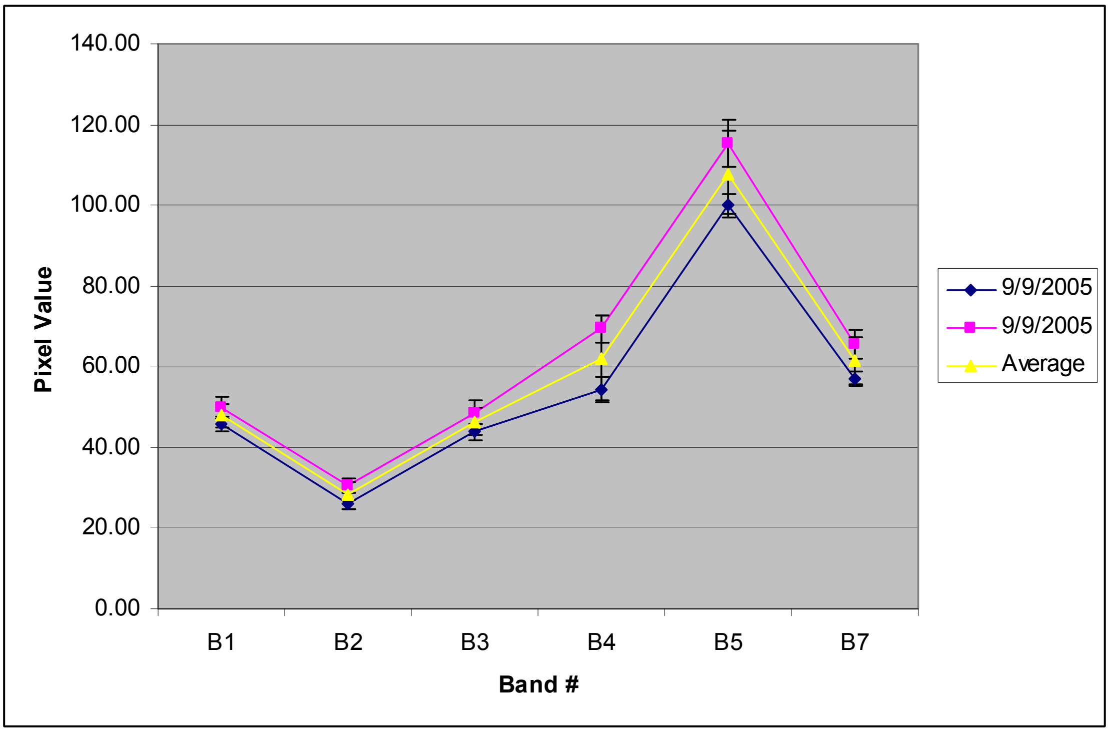


Figure 4-13: Similar to Figure 4-11, Group 2 spectral profiles and their average for two sample fields in Landsat TM images taken on September 9, 2005. The pixel value for bands 1 to 5 and band 7 were plotted. The standard deviations were plotted as the Y error bars.

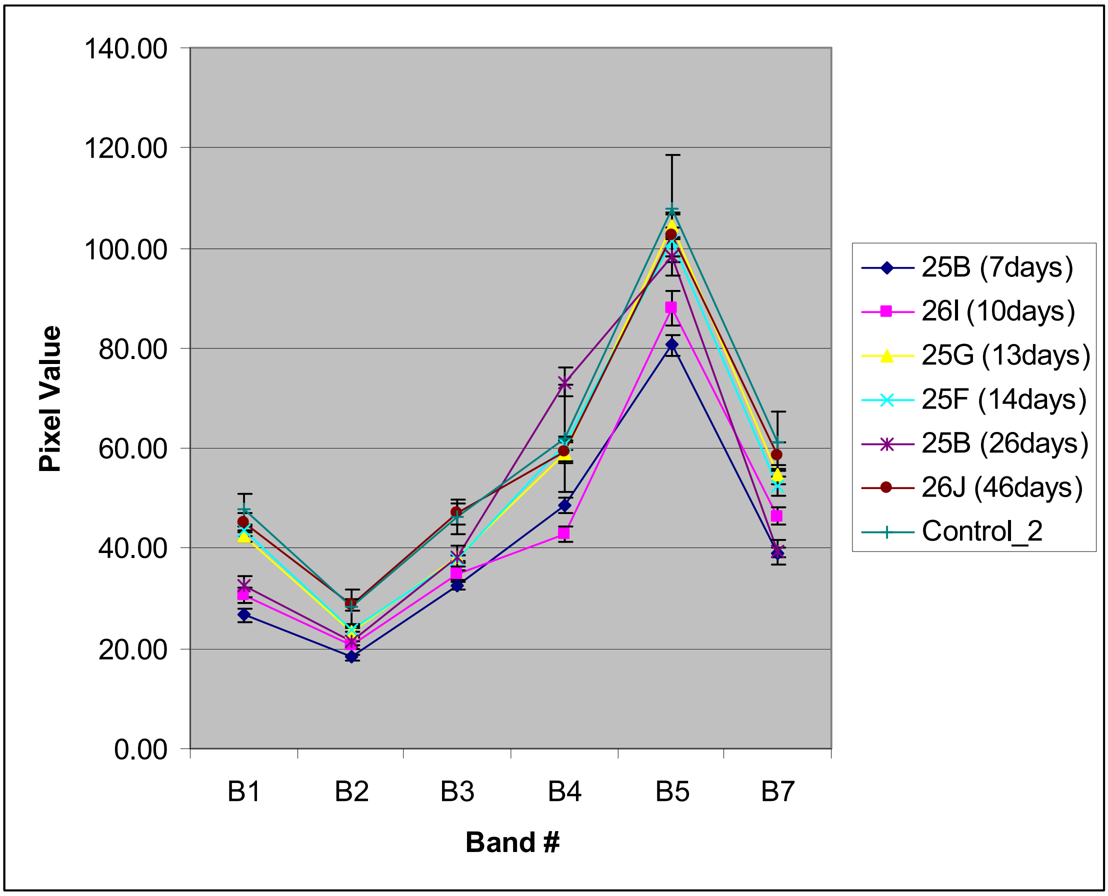


Figure 4-14: Similar to Figure 4-12, Group 2 spectral profiles for six sample study fields and the average of Group 2 control fields. The pixel value for bands 1 to 5 and band 7 were plotted. The standard deviations were plotted as the Y error bars. The number of days after sewage sludge application for each field was shown in the legend.

In Group 2, the control fields are two different fields on the same image. The average of the two control fields has bigger standard deviations than in Group 1. In Figure 4-14, we can see clearly that in band 5, the pixel values of treated fields become closer to the values of control fields from 7 days to 42 days after application. The pixel values of 25G (13 days after application), 25F (14 days after application), 25B (26 days after application) and 26J (46 days after application) are 104.41, 101.22, 98.31 and 102.39. They clump together with each other and with the value of the control field 107.82. Plus, these four values in band 5 are in the range of the standard deviation of the control field. 25B (seven days after application) and 26I (10 days after application) are not in the range of the standard deviation of control fields. Therefore, in this case, the spectral differences between control fields and treated fields can be detected up to 10 days past application. But the numbers of day after application is possibly not the only thing that affects the spectral characteristics.

In band 4, the pixel value of 25B is higher than the control fields. This may have occired because vegetation possibly started to grow on that field after sewage sludge injected. The pixel value of 25G (13 days after application), 25F (14 days after application) and 26J (46 days after application) are 59.06, 60.00 and 59.35. And the average pixel value for control fields is 61.93. The value of 26J was expected to have a bigger difference from 25G and 25F, because the image for 26J was taken one month and a half after sewage sludge injection, and the image for 25G and 25F was taken less than half month after application. But similar to band 5, they clump together with each other, and are in the range of the standard deviation of control fields. The value for 25G and 25F in band 4 were already close enough to the value of control fields. Maybe this is the reason that the value for 26J did not have a bigger difference from the value of 25G and 25F.

Most of the values of the study fields in band 7 show reasonable spectral change from 7 to 46 days after application, except 26B (26 days after application) which has a relatively low value in band 7. The pixel values of 25B (seven days after application), 26I (10 days after application), 25G (13 days after application), 25F (14 days after application) and 26J (46 days after application) are 39.20, 46.42, 54.82, 52.44 and 58.67, respectively. The value of 26J and 25G are in the range of the standard deviation of control fields. So it was hard to detect the sewage sludge injected fields in this group of data longer than 10 days by band 7.

In Group 1 (Figure 4-12), the pixel value for the study fields has large differences from the control fields in band 5 and band 7. In Group 2 (Figure 4-14), the results did not show as big a difference between study and control fields as Group 1. In Group 2, the spectral values for the study fields in band 4, band 5 and band 7 become closer and closer to the value for the control fields in 7 to 46 days after injection. In Group 1, the spectral change is also detectable in band 4. The reason why Group 1 (Figure 4-12) and Group 2 (Figure 4-14) have different spectral characteristics may be that the images were taken in different seasons. The images for Group 1 were taken in spring and the images for Group 2 were taken in fall. Considering the chronological sequence of rotation policy, sewage sludge application in spring is usually on soybean fields, and sewage sludge application in fall is on winter wheat fields. Though they are all harvested fields, there is still agricultural residue on it. Soybean fields have less residue after harvest than winter wheat fields. The soil of soybean fields may contain more nitrogen, for nitrogen fixation can be done with the growth of soybeans.

The results for these two groups indicate that the spectral difference between sewage sludge injection fields and control fields is detectable. The numbers of days that pass change the spectral characteristics of the study fields. The spectral difference between the treated and control fields can be detect up to 10 to 18 days after sewage sludge injection.

4.2 Spectral Ratios

Sridhar et al. (2006) discovered the fields with sewage sludge applied on the surface look gray, and the untreated fields look yellow. This ratio combination was proven to be able to identify sewage sludge surface application on winter wheat fields by Wang (2009). The color composite images with the spectral combinations of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, was applied to the Landsat 5 images, which were taken on April 18, 2005, May 4, 2005, September 9, 2005 and October 6, 2003. The results show that the ratio image can identify the study fields that have had sewage sludge injected and the control fields. The color of the study fields 29C, 29B, 29A, 25G, 25F, 26I and 13A were examined in the ratio combination images.

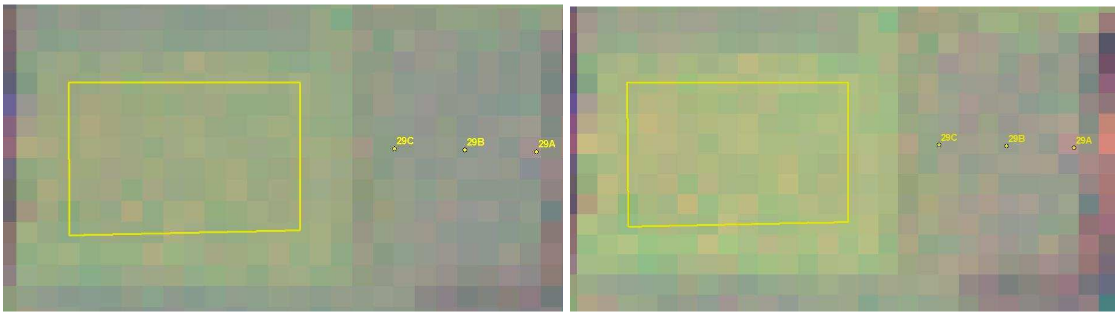
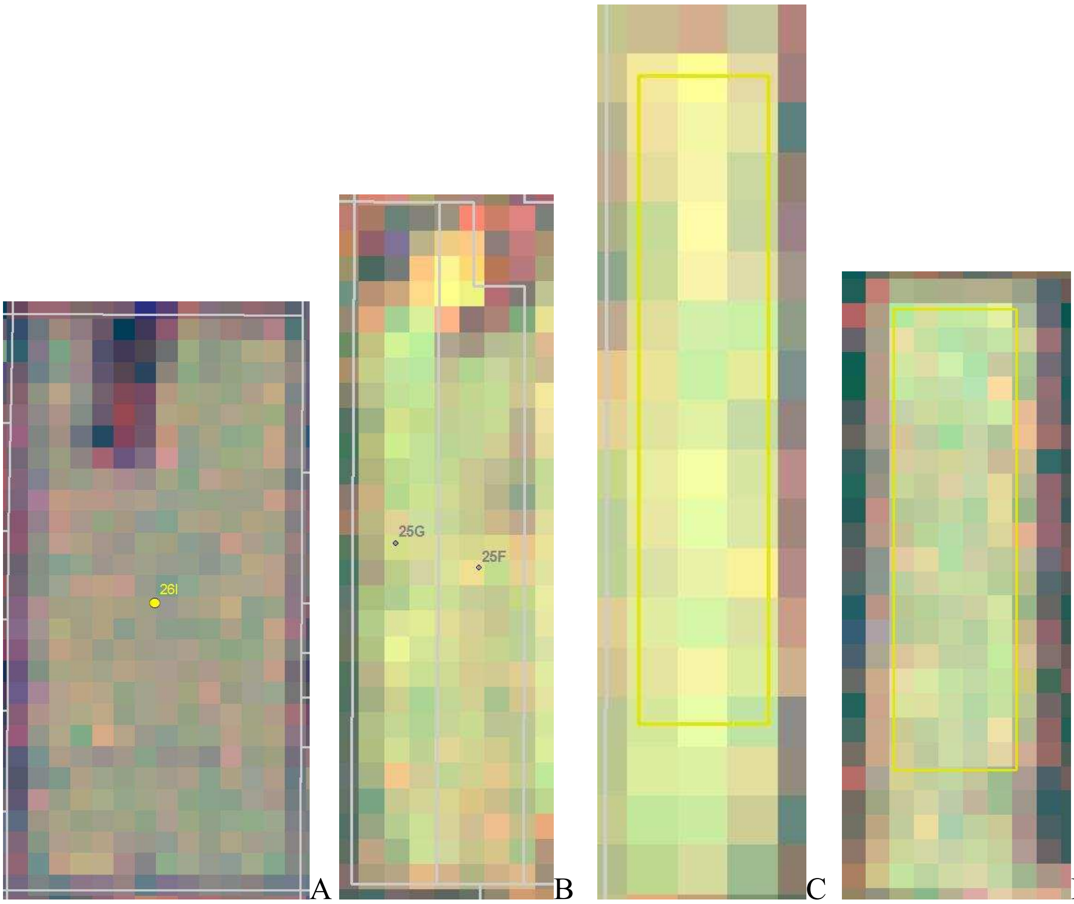


Figure 4-15: Color composite images displaying spectral ratio combinations of R(7, 5), R(5, 4) and R(3, 2) as blue, green and red, respectively for injection sewage sludge application fields on April 18, 2005 (left) and May 4, 2005 images (right). Fields 29C, 29B and 29A and the control field (in the yellow polygons) are shown.

Spectral ratio combination images of R(7, 5), R(5, 4) and R(3, 2) as blue, green and red, respectively for images taken on April 18, 2005 and May 4, 2005 images are shown in Figure 4-15. The study and control fields in the April 18, 2005 image are shown in the left image and those in May 4, 2005 image are shown in the right image. Both of them were zoomed in to the study and control fields. The sewage sludge injected fields 29C, 29B and 29A look gray, and the control fields shown in yellow rectangle look yellow. The results are the same as Sridhar et al. (2006) on sewage sludge surface application.

Looking at the left image and right image separately, it is hard to differentiate the three treated fields 29C, 29B and 29A. In the left image, sewage sludge was applied three days, four days and six days, respectively, before the image was taken. And in the right image, sewage sludge was applied 19 days, 20 days and 22 days before the image was taken. The sewage sludge application on the three study fields took place only one or two days after each other, therefore they were almost treated as one big field other than three separate fields. Comparing the treated fields on left and right images, it is obvious that the color of the treated fields changed from gray to a little bit of yellow from April 18, 2005 to May 4, 2005.



A B C D

Figure 4-16: Color composite images displaying spectral ratio combinations of R(7, 5), R(5, 4) and R(3, 2) as blue, green and red, respectively for injection sewage sludge application fields. The two images on the left-hand side show sewage sludge applied fields: A is 26I on October 6, 2003 image, B are 25G and 25F on September 9, 2005 image. The two images on the right-hand side are two control fields chosen from the September 9, 2005 image.

Figure 4-16 is another example of the study and control fields using ratio combinations. 26I had sewage sludge injected 10 days before the October 6, 2003image was taken. And 25G and 25F had sewage sludge injected 13 and 14 days, respectively, before the September 9, 2005 image was taken. C and D are two control fields on the September 9, 2005 image and they appear yellow. 26I, which appears gray in some pixels, looks more like a sewage sludge treated field. Because the October 6, 2003 image was taken only 10 days after sewage sludge was injected in 26I. 25F and 25G are more like the control fields rather than study fields. The reason could be that it was long enough after sewage sludge injection, that the spectral difference had already disappeared. Other explanations could be that the amount of sewage sludge applied on the two fields was not as much as other fields, or the weather condition around that time was detrimental to keeping the sewage sludge in soil so that the spectral difference went away.

Figure 4-15 and Figure 4-16 show the examples by using ratio combinations of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, to identify sewage sludge injection on harvested agricultural fields. The results show that the ratio combinations can identify the fields that had sewage sludge injected within 10 to 22 days in different images.

Contrast stretch was applied to the ratio images to better separate sewage sludge injected fields from other land types. The stretched images (on the left-hand side) were showed in Figure 4-17 and Figure 4-18 together with ratio combination images (in the middle) and false color images (on the right-hand side). From the stretched images, we can tell that almost all of the fields with sewage sludge injected have some light blue pixels in it. But this feature cannot distinguish the sewage sludge injection fields from all the other harvested agricultural fields because light blue pixels exist in some other fields too.

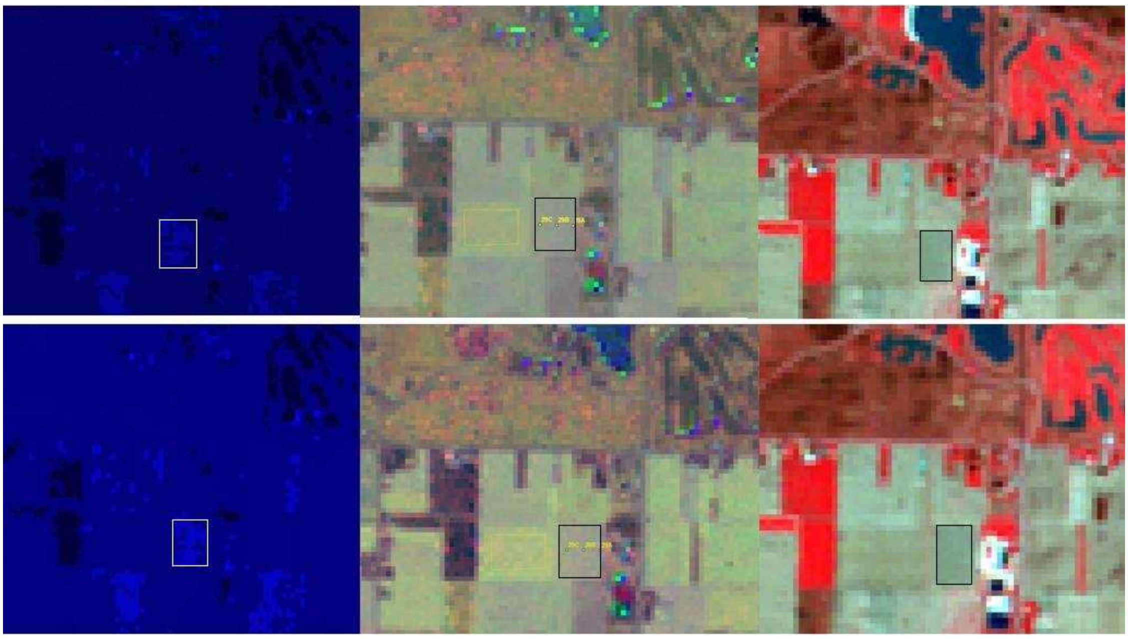


Figure 4-17: Stretched image, ratio combination image, and false color image from April 18, 2005 and May 4, 2005. The study fields 29A, 29B and 29C are in the polygons.

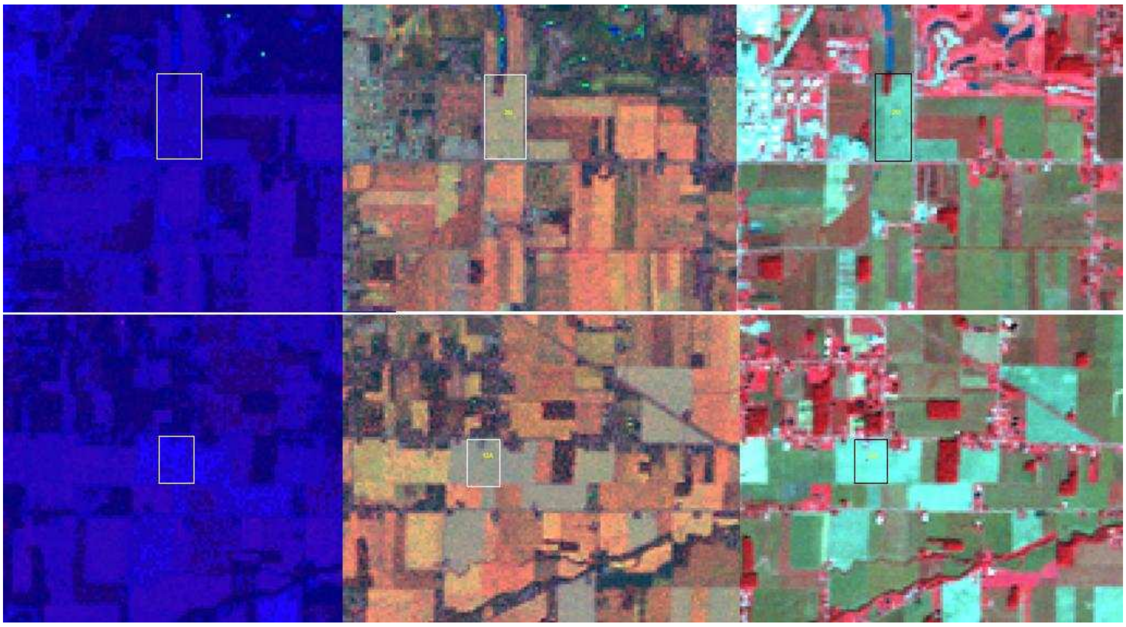


Figure 4-18: Similar to Figure 4-17, stretched image, ratio combination image, and false color image from October 6, 2003. The study fields 26I and 13A are in the polygons.

Figure 4-17 and Figure 4-18 also give a brief overview of the main steps of the thesis. The harvested agricultural fields with sewage sludge injected were found on false color images based on application records. The spectral characteristics of band 1 to band 5 and band 7 of those fields were examined. The spectral ratio combinations of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, were processed. The sewage sludge injected fields can be differentiated from the control fields, because the study fields appear gray and the control fields appear yellow. However, some other fields that are not EPA permitted fields appear gray too in Figure 4-17 and Figure 4-18. It is unlikely that these are sewage sludge applied fields. Because sewage sludge can only be applied on EPA permitted fields. Scaling the display is the reason for this problem. To highlight the study fields only, contrast stretch was applied to ratio combination images. Since no better results were gotten from the stretched images, pixel values of the study fields, the control fields and the gray but not permitted fields from ratio combination images were extracted and analyzed.

Following is the table of field-average ratio values and the standard deviations displayed as blue, green and red for each study and control field, from the four ratio combination images which were taken on April 18, 2005, May 4, 2005, September 9, 2005 and October 6, 2003. The data were plotted in Figure 4-19.

Table 4.4: Ratio value and standard deviation for the treated and control fields from image April 18, 2005, May 4, 2005, September 9, 2005 and October 6, 2003

Fields	R3/2	Standard Deviation	R5/4	Standard Deviation	R7/5	Standard Deviation
29C	1.72	0.04	2.20	0.06	0.59	0.01
29B	1.71	0.05	2.16	0.04	0.59	0.01
29A	1.69	0.06	2.16	0.07	0.59	0.01
29C	1.66	0.04	1.96	0.05	0.59	0.01
29B	1.65	0.04	1.93	0.04	0.59	0.01
29A	1.63	0.05	1.94	0.06	0.59	0.01
25F	1.61	0.05	1.61	0.08	0.51	0.01
25G	1.62	0.05	1.72	0.05	0.53	0.01
26I	1.71	0.06	2.04	0.04	0.52	0.01
13A	1.62	0.05	1.91	0.11	0.56	0.01
Control	1.82	0.03	2.52	0.03	0.55	0.01
Control	1.74	0.04	2.28	0.04	0.54	0.01
Control	1.72	0.07	2.19	0.09	0.43	0.01
Control	1.77	0.07	2.18	0.13	0.43	0.01

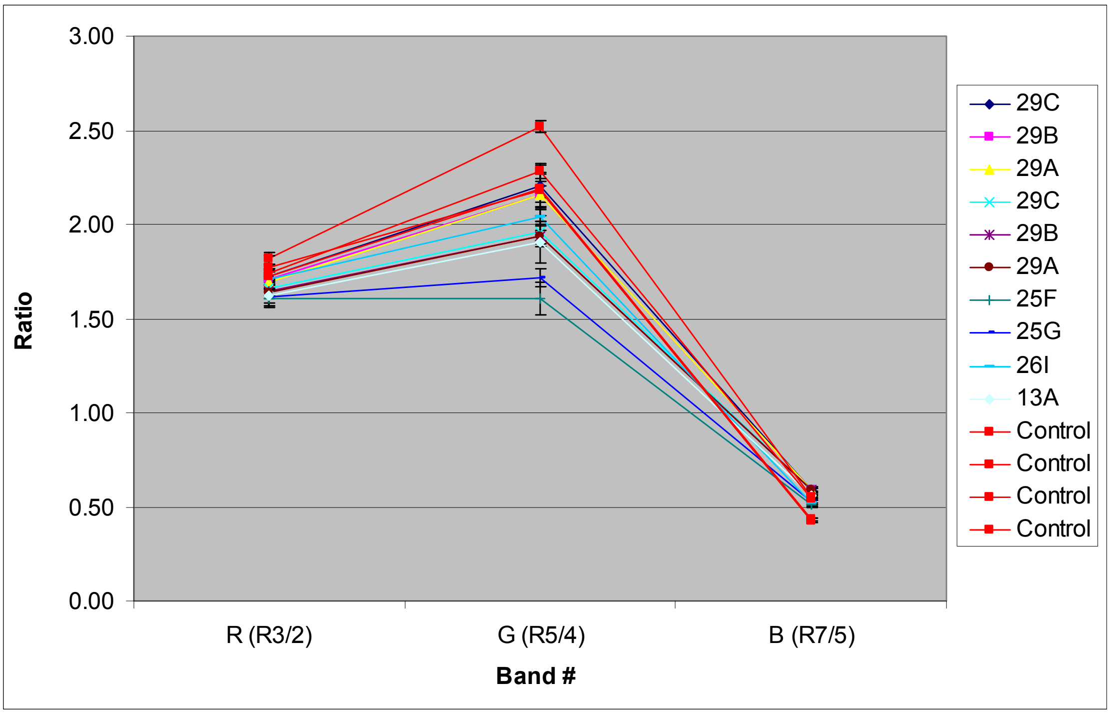


Figure 4-19: Ratio value for the study and control fields. Y error bars are the standard deviation.

Figure 4-19 shows the field-average ratio value for each study and control field. Four red lines represent the ratio values for four control fields, and other lines represent the ratio value for the study fields. The fields ID are listed in the legend. It was mentioned in Chapter 3 that spectral ratio imaging can reduce variations from environmental factors (Vincent, 1997). The ratio values for all study and control fields were listed in Table 4.4 and plotted together in Figure 4-19, regardless of the effects from different seasons or different images.

For R(3,2), the value of 29C and a control field are both 1.72. For R(5,4), the values of the study fields range from 1.61 to 2.20. Unfortunately, the values for two control fields are in the domain of the study fields. The values are 2.18 and 2.19. For R(7,5), the values of the control fields are from 0.43 to 0.55. The values of three study fields are in that domain too. They are 25F, 26I and 25G, and the values are 0.51, 0.52 and 0.53, respectively. So the field-average ratio values of R(3,2), R(5,4) and R(7,5) cannot distinguish the study fields from the control fields efficiently.

Since the field-average ratio value did not work well to divide the study and control fields, the descriptive statistics analysis were run for the pixel values from the ratio images for both study and control fields. The pixel values of 307 pixels for the study fields and 210 pixels for the control fields were processed as observed values. The mean, standard deviation, minimum, maximum and confidence level were calculated. The results were summarized in Table 4.5. And the confidence intervals at confidence level 95% of the study and control fields of three ratios are listed in Table 4.6.

Table 4.5: Mean, standard deviation, minimum, maximum, number of pixels and confidence level of the pixel value for the study and control fields from ratio combination images.

Ratios	Fields	Mean	Standard Deviation	Minimum	Maximum	Count	Confidence Level (95.0%)
R3/2	Study	1.658	0.063	1.448	1.851	307	0.007
	control	1.744	0.060	1.542	1.937	210	0.008
R5/4	Study	1.961	0.182	1.347	2.329	307	0.020
	Control	2.257	0.123	1.856	2.581	210	0.017
R7/5	Study	0.565	0.033	0.486	0.614	307	0.004
	Control	0.488	0.057	0.410	0.565	210	0.008

Table 4.6: Confidence intervals at confidence level 95% of three ratios of the study and control fields.

Ratios	R3/2	R5/4	R7/5
Study	[1.651, 1.665]	[1.941, 1.981]	[0.561, 0.569]
Control	[1.736, 1.752]	[2.240, 2.274]	[0.480, 0.496]

For R(3,2), the confidence interval at 95% confidence level for the study fields is from 1.651 to 1.665, and for the control fields is from 1.736 to 1.752. For R(5/4), the confidence interval at 95% confidence level for the study fields is from 1.941 to 1.981, and for the control fields is from 2.240 to 2.274. For R(7,5), the confidence interval at 95% confidence level for the study fields is from 0.561 to 0.569, and for the control fields is from 0.480 to 0.496. The study fields and control fields can be perfectly separated at 95% confidence level by pixel values from ratio combination images. Therefore, a pixel from ratio combination image of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, with R(3,2) value from 1.651 to 1.665, R(5,4) value from 1.941 to 1.981 and R(7,5) value from 0.561 to 0.569, at 95% confidence level, could be a spot on harvested agricultural field which may have had sewage sludge injected.

From each ratio image, three gray but not permitted fields were picked. The pixel values for those fields were extracted from the ratio combination images. A total of 1130 pixels for gray but not permitted fields were processed as observed values. The mean, standard deviation, minimum, maximum and confidence level were calculated. The results were summarized in Table 4.7. And the confidence intervals at confidence level 95% of the study and control fields of three ratios are listed in Table 4.8.

Table 4.7: Mean, standard deviation, minimum, maximum, number of pixels and confidence level of the pixel value for gray but not permitted fields from ratio combination images

Ratios	Mean	Standard Deviation	Minimum	Maximum	Count	Confidence Level (95.0%)
R3/2	1.682	0.137	1.449	2.252	1130	0.008
R5/4	1.971	0.103	1.706	2.232	1130	0.006
R7/5	0.576	0.052	0.414	0.638	1130	0.003

Table 4.8: Confidence intervals at confidence level 95% of three ratios of gray but not permitted fields

Ratios	R3/2	R5/4	R7/5
Confidence Interval	[1.674, 1.690]	[1.965, 1.977]	[0.573, 0.579]

Compared to the confidence intervals of three ratios for both study and control fields (Table 4.6), the confidence intervals of R (3, 2) and R (7, 5) for gray but not permitted fields are not in the intervals of study nor control fields. But the confidence interval of R(5,4) of the gray but not permitted fields is in the interval of the study fields. Therefore, to confirm a pixel is representing a spot in a treated field, the pixel value from the ratio combination image must meet the following three conditions at the same time: R(3,2) value is in the interval of 1.651 to 1.665, R(5,4) value is in the interval of 1.941 to 1.981 and R(7,5) value is in the interval of 0.561 to 0.569, at 95% confidence level.

To summarize, by visually testing the color of the ratio combination image, the treated fields look gray, and the control fields look yellow. By plotting the fields-average values from the ratio images, the ratios of R(7,5), R(5,4) and R(3,2), cannot distinguish all the sewage sludge injected fields from the control fields efficiently. By running the descriptive statistics analysis, the confidence interval for the study and control fields of R(3,2), R(5,4) and R(7,5) at 95% confidence level, can better identify the study fields out of the control fields. Therefore, the spectral ratio combination of R(7,5), R(5,4) and R(3,2) can be used to identify sewage sludge injection application.

Chapter 5

Conclusion and Discussion

Application of sewage sludge to agricultural fields is beneficial. Yet the heavy metals, pathogens and nutrients in sewage sludge may bring potential risks to public health. To address this problem, we need to know where sewage sludge has been applied. However, the difficulty in getting a complete record of sewage sludge application pushed us to identify sewage sludge application by remote sensing technology. Sridhar et al. (2006) and Wang (2009) successfully identified sewage sludge surface application using spectral ratio combination of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively. This method was tested in this research to identify the sewage sludge injection application. The results indicate that the harvested agricultural fields with sewage sludge injected can be identify by spectral ratio combination of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, using Landsat TM imagery.

The following steps were taken to identify sewage sludge injection application. Selected images were subset into the area of interest and atmospheric correction were processed to reduce the atmospheric effects and increase the image accuracy. Based on sewage sludge application records, the study and control fields were located on harvested agricultural fields. Pixel values for band 1 to 5 and 7 were extracted from the false color images, and plotted to compare the spectral differences between the treated and control fields. The results of this study indicate that the fields with injection sewage sludge application can be distinguished by Landsat 5 TM imagery from the control fields. This was shown through differences in pixel values in bands 4, 5 and 7. For some fields, the pixel value in band 5, digital number, for the study field is 40 lower than the control field. The differences become harder to detect after 18 days past application in Group1, and 10 days past application in Group 2. In addition to the period of time after application, there are other factors that may affect the spectral characteristics, such as seasons, crops, residues and soils.

Ratio combination of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, were applied to four images. The color of the fields with sewage sludge injected and the control fields were examined. The ratio images were stretched to highlight the study fields out of all other land types. The pixel values of the study fields and the control fields were extracted and ratio images were produced. The field-average pixel values were plotted to find the spectral differences between the study and control fields. Confidence intervals with a confidence level at 95% of the pixel values of three ratios were calculated for the study fields, the control fields and the fields that look like study fields.

The spectral ratio combination of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, can be used to visually identify the sewage sludge injection applied fields out of the control fields. In the spectral ratio images, the study fields appear gray, and the control fields appear yellow. The spectral change can be shown by color too. However, because of scaling, some fields that are not EPA permitted fields appeared gray too. Contrast stretch was applied to ratio combination images to highlight the study fields only. Since no better results were gotten from the stretched images, pixel values of the study fields, the control fields and the gray but not permitted fields from ratio combination images were extracted. The field-average ratio values of R(3,2), R(5,4) and R(7,5) cannot distinguish the study fields from the control fields efficiently, for some of the study fields and the control fields have similar field-average ratio values.

The confidence intervals with a confidence level at 95% of the three ratios were calculated for both treated and untreated fields. For R(3,2), the confidence interval of the study fields is from 1.651 to 1.665, and that of the control fields is from 1.736 to 1.752. For R(5/4), the confidence interval of the study fields is from 1.941 to 1.981, and that of the control fields is from 2.240 to 2.274. For R(7,5), the confidence interval of the study fields is from 0.561 to 0.569, and that of the control fields is from 0.480 to 0.496. Therefore, the confidence interval of the pixel value can separate the study and control fields better than the field-average ratio values. For the gray but not permitted fields, the confidence interval for each ratio was calculated too. For R(3,2) the confidence interval is from 1.674 to 1.690. For R(5,4), the confidence interval is from 1.965 to 1.977. And for R(7,5) the confidence interval is from 0.573 to 0.579. Except R(5,4), the other two confidence intervals do not overlap with the intervals from the study fields. Therefore, to confirm a pixel is representing a spot in a treated field, the pixel value from the ratio combination image must meet the following three conditions at the same time: R(3,2) value is in the interval of 1.651 to 1.665, R(5,4) value is in the interval of 1.941 to 1.981 and R(7,5) value is in the interval of 0.561 to 0.569, at 95% confidence level.

To sum up, the harvested agricultural fields with sewage sludge injected can be identify by spectral ratio combination of R(7,5), R(5,4) and R(3,2) displayed as blue, green and red, respectively, using Landsat TM imagery.

There are issues that need to be considered in this study. In Sridhar et al. (2006), they chose one study field and the images before and after sewage sludge application for that field. They went to the field and they knew the crop was winter wheat. Plus they did several kinds of samplings, and examined the spectral reflectance both in field and in the lab. There are several confounding factors in this study. Not all of the sewage sludge applied fields and the control fields used in this study have been verified to be winter wheat harvested fields. Because we only have part of the crop classification file for 2005 and 2006, the images and sewage sludge application data used in this study are from 2003 to 2005. Second, since sewage sludge application data for 1999 to 2002 was not available, it was decided to use the data after 2003. Third, the selection of control fields may also bring errors, for different weather conditions and different seasons could affect the spectral characteristics extracted from the imagery. Fourth, sewage sludge injection application is different from surface application, and the field may exhibit different spectral characteristics.

For this ongoing project, more research needs to be conducted. The selection of the study and control fields could be optimized. The spectral change of one study field before and after sewage sludge application could be observed by several satellite images. Table 5.1 shows the images that are available on OhioView and the study fields that could be observed.

Table 5.1: The study fields and the landsat 5 images that are available before and after the sewage sludge application on those fields

Study Field	Images			
29C	4/18/2005 (3days)	5/4/2005 (19 days)	5/20/2005 (35 days)	
29B	4/18/2005 (4 days)	5/4/2005 (20 days)	5/20/2005 (26 days)	
29A	4/18/2005 (6 days)	5/4/2005 (22 days)	5/20/2005 (38 days)	
25B	8/5/2004 (10days)	8/21/2004 (26days)	9/6/2004 (42days)	
26J	7/22/2004 (before app)	8/5/2004 (14days)	8/21/2004 (30 days)	9/6/2004 (46days)

Multi-variable regression needs to be done based on the pixel value extracted from the spectral ratio combination images. The ratio values could be the dependent variables, and the amount of sewage sludge application or certain elements in soil due to the sewage sludge application, as Phosphorus, Lead or cadmium, could be the independent variable. The decision tree for identifying the sewage sludge injection application should be made in Knowledge Engineer in Erdas Imagine, based on the confidence intervals in this study, to see if the fields with sewage sludge injected can be successfully classified or not.

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Appendix A

Spectral Characteristics for Study and Control fields

Table A.1: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 29C on Landsat 5 image taken on April 18, 2005.

X	Y	B1	B2	B3	B4	B5	B7
302190	4615890	33	26	45	58	122	74
302220	4615890	32	27	48	57	124	73
302190	4615860	33	27	45	58	129	77
302220	4615860	32	27	46	58	127	76
302190	4615830	30	27	46	58	131	77
302220	4615830	32	26	46	59	125	76
302190	4615800	31	27	46	57	126	75
302220	4615800	32	26	45	59	123	74
302190	4615770	34	27	46	57	125	73
302220	4615770	31	27	47	60	130	76
302190	4615740	34	26	46	57	128	75
302220	4615740	32	27	45	58	126	75
302190	4615710	33	26	46	58	133	75
302220	4615710	32	27	45	57	130	76
302190	4615680	32	26	46	57	129	74
302220	4615680	32	27	47	58	126	75
302190	4615650	31	26	46	58	129	74
302220	4615650	31	26	47	59	129	75
302190	4615620	31	27	45	56	130	77
302220	4615620	28	26	45	57	127	75
Average		31.80	26.55	45.90	57.80	127.45	75.10
Standard Deviation		1.63	0.51	0.85	0.95	2.84	1.21

Table A.2: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 29B on Landsat 5 image taken on April 18, 2005.

X	Y	B1	B2	B3	B4	B5	B7
302250	4615890	34	27	47	58	130	75
302280	4615890	33	29	47	59	129	75
302310	4615890	32	27	47	59	126	73
302250	4615860	34	28	48	60	130	78
302280	4615860	38	29	48	61	128	77
302310	4615860	37	27	47	61	129	75
302250	4615830	33	27	46	59	126	74
302280	4615830	36	28	48	59	127	76
302310	4615830	35	29	47	60	128	76
302250	4615800	33	27	46	59	131	73
302280	4615800	33	28	47	61	127	76
302310	4615800	35	27	47	60	128	77
302250	4615770	32	27	47	58	130	75
302280	4615770	32	28	47	58	127	76
302310	4615770	31	27	47	59	129	78
302250	4615740	33	27	46	58	127	75
302280	4615740	33	27	47	58	129	78
302310	4615740	32	28	49	60	131	78
302250	4615710	34	26	46	58	130	74
302280	4615710	33	27	45	59	129	76
302310	4615710	30	27	45	60	131	77
302250	4615680	32	26	47	59	127	75
302280	4615680	30	27	47	59	127	78
302310	4615680	32	27	48	59	130	79
302250	4615650	31	27	46	58	127	75
302280	4615650	30	27	45	60	127	76
302310	4615650	31	28	47	61	130	79
302250	4615620	31	27	48	60	127	76
302280	4615620	33	28	48	61	128	77
302310	4615620	31	28	47	61	132	79
Average		32.80	27.40	46.90	59.40	128.57	76.20
Standard Deviation		1.97	0.77	0.96	1.07	1.65	1.69

Table A.3: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 29A on Lansat 5 image taken on April 18, 2005.

X	Y	B1	B2	B3	B4	B5	B7
302310	4615920	37	28	46	60	140	79
302340	4615920	36	28	48	64	140	81
302370	4615920	36	30	48	63	136	78
302310	4615890	32	27	47	59	126	73
302340	4615890	32	29	47	61	128	74
302370	4615890	34	28	48	61	130	76
302310	4615860	37	27	47	61	129	75
302340	4615860	34	28	46	61	130	75
302370	4615860	36	28	48	61	131	76
302310	4615830	35	29	47	60	128	76
302340	4615830	32	30	48	61	135	80
302370	4615830	36	29	47	57	130	76
302310	4615800	35	27	47	60	128	77
302340	4615800	36	28	49	61	134	80
302370	4615800	33	27	49	57	127	76
302310	4615770	31	27	47	59	129	78
302340	4615770	34	29	48	63	134	80
302370	4615770	34	28	52	65	131	79
302310	4615740	32	28	49	60	131	78
302340	4615740	33	29	51	63	137	80
302370	4615740	34	30	49	67	133	81
302310	4615710	30	27	45	60	131	77
302340	4615710	32	28	47	62	136	80
302370	4615710	33	30	50	63	137	80
302310	4615680	32	27	48	59	130	79
302340	4615680	30	28	47	63	133	79
302370	4615680	36	31	53	60	135	79
302310	4615650	31	28	47	61	130	79
302340	4615650	31	29	47	62	137	80
302370	4615650	33	31	51	62	138	78
302310	4615620	31	28	47	61	132	79
302340	4615620	32	28	50	61	136	78
302370	4615620	33	31	52	65	132	75
Average		33.42	28.48	48.24	61.30	132.55	77.91
Standard Deviation		2.05	1.23	1.89	2.14	3.78	2.11

Table A.4: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 25B on Landsat 5 image taken on September 22, 2004.

X	Y	B1	B2	B3	B4	B5	B7
299100	4616730	25	17	32	48	80	39
299130	4616730	27	18	32	49	81	39
299160	4616730	27	19	32	50	81	42
299190	4616730	25	19	32	50	80	41
299220	4616730	25	18	32	50	79	38
299100	4616700	29	18	32	47	80	39
299130	4616700	27	18	32	48	78	40
299160	4616700	26	19	33	50	80	38
299190	4616700	25	20	33	51	82	38
299220	4616700	25	19	33	52	83	39
299100	4616670	27	18	32	48	81	39
299130	4616670	27	18	32	48	80	40
299160	4616670	28	18	32	49	80	38
299190	4616670	29	19	32	48	82	39
299220	4616670	26	18	32	51	83	40
299100	4616640	23	18	32	48	78	38
299130	4616640	26	18	32	47	80	38
299160	4616640	27	18	33	48	79	39
299190	4616640	28	18	32	47	79	41
299220	4616640	26	18	32	50	82	39
299100	4616610	26	18	32	49	80	40
299130	4616610	28	18	33	49	83	40
299160	4616610	27	19	33	49	84	40
299190	4616610	30	19	34	47	82	41
299220	4616610	27	18	32	47	81	40
299100	4616580	28	18	33	48	79	39
299130	4616580	28	19	35	51	81	38
299160	4616580	27	19	34	51	85	38
299190	4616580	26	18	33	49	83	41
299220	4616580	26	17	33	47	81	38
299100	4616550	25	18	32	46	78	39
299130	4616550	27	18	34	48	82	40
299160	4616550	27	18	34	49	82	40
299190	4616550	28	19	33	48	82	40
299220	4616550	28	18	31	47	80	39
299100	4616520	26	18	32	46	74	37
299130	4616520	26	18	33	47	78	38
299160	4616520	27	18	33	47	80	39
299190	4616520	27	17	33	47	80	38
299220	4616520	25	18	32	49	80	39
Average		26.68	18.23	32.58	48.50	80.58	39.20
Standard Deviation		1.37	0.62	0.81	1.50	1.99	1.11

Table A.5: Pixel value, average pixel value and standard deviation for sewage sludge injection application field 26I on Landsat 5 image taken on October 6, 2003.

X	Y	B1	B2	B3	B4	B5	B7
296970	4616220	31	22	39	52	103	46
297000	4616220	33	24	40	55	114	54
297030	4616220	32	23	40	53	109	53
297060	4616220	32	21	39	51	111	52
296970	4616190	33	23	42	55	109	52
297000	4616190	33	24	41	56	113	56
297030	4616190	29	22	40	52	111	53
297060	4616190	33	25	40	54	112	53
296970	4616160	34	25	43	58	120	56
297000	4616160	33	23	42	55	117	56
297030	4616160	33	23	40	55	112	54
297060	4616160	32	23	41	55	115	56
296970	4616130	34	25	42	57	119	55
297000	4616130	33	25	43	57	120	57
297030	4616130	34	24	44	57	121	57
297060	4616130	35	24	43	58	119	57
296970	4616100	34	23	40	54	108	52
297000	4616100	31	25	41	58	123	56
297030	4616100	33	23	43	57	125	55
297060	4616100	34	22	41	57	121	54
296970	4616070	31	22	39	55	101	49
297000	4616070	32	24	41	56	117	51
297030	4616070	33	24	42	55	118	54
297060	4616070	31	23	39	56	117	54
296970	4616040	31	22	41	51	111	54
297000	4616040	32	23	40	50	111	55
297030	4616040	35	23	40	52	110	55
297060	4616040	34	23	41	54	112	56
Average		32.68	23.32	40.96	54.82	114.25	54.00
Standard Deviation		1.39	1.09	1.40	2.28	5.79	2.49

Table A.6: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 25G on Landsat 5 image taken on September 9, 2005.

X	Y	B1	B2	B3	B4	B5	B7
298410	4616250	43	24	38	58	103	57
298440	4616250	45	25	39	54	97	55
298410	4616220	43	24	38	62	108	57
298440	4616220	43	24	38	58	104	55
298410	4616190	41	23	38	61	107	53
298440	4616190	43	24	38	60	103	50
298410	4616160	43	24	39	59	109	55
298440	4616160	43	24	38	60	105	56
298410	4615950	43	22	37	60	106	58
298440	4615950	42	23	39	56	103	54
298470	4615950	44	23	39	59	101	54
298410	4615920	43	22	38	56	107	57
298440	4615920	41	23	38	58	103	55
298470	4615920	43	23	38	60	104	55
298410	4615890	40	22	37	60	105	53
298440	4615890	42	23	37	60	104	54
298470	4615890	41	24	39	63	106	54
Average		42.53	23.35	38.12	59.06	104.41	54.82
Standard Deviation		1.23	0.86	0.70	2.25	2.83	1.91

Table A.7: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 25F on Landsat 5 image taken on September 9, 2005.

X	Y	B1	B2	B3	B4	B5	B7
298410	4616220	43	24	38	62	108	57
298470	4616220	45	23	37	62	98	50
298500	4616220	44	24	38	62	103	52
298530	4616220	44	24	38	59	101	53
298470	4616190	43	24	38	62	99	51
298500	4616190	43	24	38	62	102	53
298530	4616190	44	23	37	59	100	52
298470	4616160	43	25	39	60	99	51
298500	4616160	42	24	38	61	101	53
Average		43.44	23.89	37.89	61.00	101.22	52.44
Standard Deviation		0.88	0.60	0.60	1.32	2.99	2.01

Table A.8: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 35C on Landsat 5 image taken on June 11, 2007.

X	Y	B1	B2	B3	B4	B5	B7
296610	4615260	44	26	45	56	122	74
296640	4615260	45	29	51	63	133	82
296670	4615260	47	32	55	67	143	85
296610	4615230	44	27	48	59	126	79
296640	4615230	47	29	52	65	135	83
296670	4615230	50	34	60	71	144	88
296610	4615200	47	26	47	60	128	77
296640	4615200	48	28	51	63	133	80
296670	4615200	49	32	57	68	140	85
296610	4615170	46	26	45	57	121	74
296640	4615170	46	27	47	62	129	74
296670	4615170	47	29	52	68	147	86
296610	4615140	45	27	46	60	122	73
296640	4615140	46	28	48	65	144	82
296670	4615140	48	29	50	64	156	89
296610	4615110	48	28	49	71	149	86
296640	4615110	47	28	50	73	160	90
296670	4615110	47	29	49	65	144	81
296610	4615080	46	28	49	67	146	82
296640	4615080	45	26	48	62	137	78
296670	4615080	46	28	48	62	130	78
296610	4615050	44	28	47	61	126	75
296640	4615050	44	27	46	59	118	70
296670	4615050	45	28	46	59	123	72
296610	4615020	43	26	47	61	123	75
296640	4615020	45	28	47	61	121	72
296670	4615020	46	28	48	59	124	75
296610	4614990	45	27	48	60	124	74
296640	4614990	47	27	47	62	125	74
296670	4614990	46	28	49	62	127	76
296610	4614960	47	29	48	62	124	74
296640	4614960	46	29	48	63	126	75
296670	4614960	47	29	49	62	131	76
296610	4614930	44	27	49	62	127	75
296640	4614930	45	28	48	62	124	75
296670	4614930	47	30	50	65	132	78
Average		46.08	28.19	49.00	63.00	132.33	78.39
Standard Deviation		1.54	1.74	3.13	3.87	10.71	5.33

Table A.9: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 29C on Landsat 5 image taken on May 4, 2005.

X	Y	B1	B2	B3	B4	B5	B7
302190	4615890	44	30	50	65	122	74
302220	4615890	43	31	53	64	124	73
302190	4615860	44	31	50	65	129	77
302220	4615860	43	31	51	65	127	76
302190	4615830	41	31	51	65	131	77
302220	4615830	43	30	51	66	125	76
302190	4615800	42	31	51	64	126	75
302220	4615800	43	30	50	66	123	74
302190	4615770	45	31	51	64	125	73
302220	4615770	42	31	52	67	130	76
302190	4615740	45	30	51	64	128	75
302220	4615740	43	31	50	65	126	75
302190	4615710	44	30	51	65	133	75
302220	4615710	43	31	50	64	130	76
302190	4615680	43	30	51	64	129	74
302220	4615680	43	31	52	65	126	75
302190	4615650	42	30	51	65	129	74
302220	4615650	42	30	52	66	129	75
302190	4615620	42	31	50	63	130	77
302220	4615620	39	30	50	64	127	75
Average		42.80	30.55	50.90	64.80	127.45	75.10
Standard Deviation		1.36	0.51	0.85	0.95	2.84	1.21

Table A.10: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 29B on Landsat 5 image taken on May 4, 2005.

X	Y	B1	B2	B3	B4	B5	B7
302250	4615890	45	31	52	65	130	75
302280	4615890	44	33	52	66	129	75
302310	4615890	43	31	52	66	126	73
302250	4615860	45	32	53	67	130	78
302280	4615860	49	33	53	68	128	77
302310	4615860	48	31	52	68	129	75
302250	4615830	44	31	51	66	126	74
302280	4615830	47	32	53	66	127	76
302310	4615830	46	33	52	67	128	76
302250	4615800	44	31	51	66	131	73
302280	4615800	44	32	52	68	127	76
302310	4615800	46	31	52	67	128	77
302250	4615770	43	31	52	65	130	75
302280	4615770	43	32	52	65	127	76
302310	4615770	42	31	52	66	129	78
302250	4615740	44	31	51	65	127	75
302280	4615740	44	31	52	65	129	78
302310	4615740	43	32	54	67	131	78
302250	4615710	45	30	51	65	130	74
302280	4615710	44	31	50	66	129	76
302310	4615710	41	31	50	67	131	77
302250	4615680	43	30	52	66	127	75
302280	4615680	41	31	52	66	127	78
302310	4615680	43	31	53	66	130	79
302250	4615650	42	31	51	65	127	75
302280	4615650	41	31	50	67	127	76
302310	4615650	42	32	52	68	130	79
302250	4615620	42	31	53	67	127	76
302280	4615620	44	32	53	68	128	77
302310	4615620	42	32	52	68	132	79
Average		43.80	31.40	51.90	66.40	128.57	76.20
Standard Deviation		1.97	0.77	0.96	1.07	1.65	1.69

Table A.11: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 29A on Landsat 5 image taken on May 4, 2005.

X	Y	B1	B2	B3	B4	B5	B7
302310	4615920	48	32	51	67	140	79
302340	4615920	47	32	53	71	140	81
302370	4615920	47	34	53	70	136	78
302310	4615890	43	31	52	66	126	73
302340	4615890	43	33	52	68	128	74
302370	4615890	45	32	53	68	130	76
302310	4615860	48	31	52	68	129	75
302340	4615860	45	32	51	68	130	75
302370	4615860	47	32	53	68	131	76
302310	4615830	46	33	52	67	128	76
302340	4615830	43	34	53	68	135	80
302370	4615830	47	33	52	64	130	76
302310	4615800	46	31	52	67	128	77
302340	4615800	47	32	54	68	134	80
302370	4615800	44	31	54	64	127	76
302310	4615770	42	31	52	66	129	78
302340	4615770	45	33	53	70	134	80
302370	4615770	45	32	57	72	131	79
302310	4615740	43	32	54	67	131	78
302340	4615740	44	33	56	70	137	80
302370	4615740	45	34	54	74	133	81
302310	4615710	41	31	50	67	131	77
302340	4615710	43	32	52	69	136	80
302370	4615710	44	34	55	70	137	80
302310	4615680	43	31	53	66	130	79
302340	4615680	41	32	52	70	133	79
302370	4615680	47	35	58	67	135	79
302310	4615650	42	32	52	68	130	79
302340	4615650	42	33	52	69	137	80
302370	4615650	44	35	56	69	138	78
302310	4615620	42	32	52	68	132	79
302340	4615620	43	32	55	68	136	78
302370	4615620	44	35	57	72	132	75
Average		44.42	32.48	53.24	68.30	132.55	77.91
Standard Deviation		2.05	1.23	1.89	2.14	3.78	2.11

Table A.12: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 25B on Landsat 5 image taken on August 21, 2004.

X	Y	B1	B2	B3	B4	B5	B7
299130	4616700	33	22	39	68	101	40
299160	4616700	29	21	36	70	100	41
299190	4616700	30	20	35	74	93	38
299220	4616700	29	20	35	76	93	34
299130	4616670	32	21	39	72	100	40
299160	4616670	36	22	39	71	98	42
299190	4616670	32	20	35	74	93	36
299220	4616670	32	21	36	77	93	36
299130	4616640	34	22	40	73	103	41
299160	4616640	35	22	40	71	104	43
299190	4616640	31	21	36	74	97	38
299220	4616640	32	21	37	79	95	38
299130	4616610	31	23	41	73	101	39
299160	4616610	35	22	42	70	103	40
299190	4616610	35	22	40	73	100	41
299220	4616610	33	22	39	77	99	41
Average		32.44	21.38	38.06	73.25	98.31	39.25
Standard Deviation		2.16	0.89	2.32	2.96	3.88	2.44

Table A.13: Pixel values, average pixel value and standard deviation for sewage sludge injection application field 26J on Landsat 5 image taken on September 6, 2004.

X	Y	B1	B2	B3	B4	B5	B7
297450	4616310	46	28	45	57	97	57
297480	4616310	43	27	44	57	98	56
297510	4616310	44	27	46	57	99	56
297540	4616310	47	29	48	59	102	62
297570	4616310	45	29	48	61	104	60
297600	4616310	48	31	52	65	112	66
297630	4616310	45	31	50	62	111	62
297660	4616310	43	28	46	61	106	61
297690	4616310	41	27	46	60	104	62
297450	4616280	45	27	46	58	102	56
297480	4616280	45	28	46	58	99	57
297510	4616280	46	28	46	58	99	57
297540	4616280	47	29	47	60	101	60
297570	4616280	46	29	48	61	104	57
297600	4616280	45	30	50	63	111	65
297630	4616280	44	29	50	61	108	61
297660	4616280	45	27	46	60	105	61
297690	4616280	44	28	47	60	107	61
297450	4616250	44	27	46	58	100	57
297480	4616250	45	29	47	58	100	58
297510	4616250	45	28	45	58	103	59
297540	4616250	45	29	46	58	98	58
297570	4616250	45	29	47	59	105	58
297600	4616250	47	30	48	62	107	63
297630	4616250	47	29	47	61	106	61
297660	4616250	45	29	47	61	104	60
297690	4616250	47	30	50	61	104	61
297450	4616220	48	28	46	59	102	59
297480	4616220	49	29	46	59	102	59
297510	4616220	44	28	45	58	102	59
297540	4616220	45	29	46	57	100	56
297570	4616220	45	29	45	59	100	56
297600	4616220	47	32	51	63	106	62
297630	4616220	47	29	51	63	108	62
297660	4616220	48	29	49	62	103	60
297690	4616220	48	28	48	60	104	59
297450	4616190	45	28	47	60	106	61
297480	4616190	46	29	47	60	104	61
297510	4616190	47	28	46	59	103	58
297540	4616190	46	28	46	58	102	60
297570	4616190	46	28	46	60	102	58
297600	4616190	44	30	50	63	107	61
297630	4616190	49	31	51	63	109	60

297660	4616190	46	29	49	61	103	58
297690	4616190	45	30	47	59	103	58
297450	4616160	45	28	46	60	104	60
297480	4616160	44	29	46	59	106	61
297510	4616160	44	29	46	58	103	59
297540	4616160	44	28	46	59	105	59
297570	4616160	45	28	47	59	100	59
297600	4616160	46	30	49	62	105	59
297630	4616160	46	32	51	62	106	59
297660	4616160	44	30	51	63	105	60
297690	4616160	44	29	47	59	102	58
297450	4616130	46	28	44	58	100	57
297480	4616130	49	29	47	59	102	59
297510	4616130	48	28	45	57	100	58
297540	4616130	44	28	45	57	102	58
297570	4616130	42	28	46	58	102	58
297600	4616130	44	28	46	60	104	57
297630	4616130	42	29	46	60	99	56
297660	4616130	42	27	45	56	96	56
297690	4616130	45	28	47	58	102	58
297450	4616100	42	27	43	58	93	56
297480	4616100	44	28	44	57	98	56
297510	4616100	43	27	44	56	100	56
297540	4616100	43	27	45	55	97	57
297570	4616100	43	28	46	56	97	57
297600	4616100	44	28	47	58	101	56
297630	4616100	42	28	45	58	100	51
297660	4616100	42	26	44	56	86	50
297690	4616100	46	29	46	58	95	55
Average		45.10	28.58	46.86	59.35	102.39	58.67
Standard Deviation		1.84	1.18	2.01	2.08	4.19	2.64

Table A.14: Pixel values, average pixel value and standard deviation for control field on Landsat 5 image taken on April 18, 2005.

X	Y	B1	B2	B3	B4	B5	B7
301710	4615830	34	29	52	70	172	95
301740	4615830	35	27	51	69	171	92
301770	4615830	35	28	52	68	169	91
301800	4615830	36	29	52	69	170	90
301830	4615830	36	28	50	67	171	89
301860	4615830	35	27	47	66	168	91
301890	4615830	37	27	49	66	164	90
301920	4615830	34	27	50	68	169	93
301950	4615830	32	29	50	68	173	94
301980	4615830	32	29	50	68	174	95
302010	4615830	34	29	51	69	176	95
302040	4615830	32	27	49	67	174	94
301710	4615800	34	28	51	69	175	95
301740	4615800	34	26	51	67	167	90
301770	4615800	34	26	49	67	166	90
301800	4615800	34	28	51	68	169	93
301830	4615800	34	27	50	67	169	90
301860	4615800	33	26	48	66	168	92
301890	4615800	36	25	47	65	166	89
301920	4615800	33	27	48	66	167	91
301950	4615800	33	28	49	67	170	94
301980	4615800	33	28	50	67	173	95
302010	4615800	34	27	50	67	173	94
302040	4615800	32	27	49	67	172	94
301710	4615770	32	27	49	69	173	93
301740	4615770	31	26	49	67	169	91
301770	4615770	31	25	47	66	165	89
301800	4615770	32	26	48	65	162	90
301830	4615770	33	27	47	66	166	90
301860	4615770	32	26	48	65	165	91
301890	4615770	32	25	47	63	165	89
301920	4615770	29	26	47	64	165	91
301950	4615770	33	26	47	65	166	90
301980	4615770	31	26	47	65	165	93
302010	4615770	31	27	48	65	167	92
302040	4615770	33	26	48	65	167	92
301710	4615740	34	27	50	70	175	93
301740	4615740	33	26	48	67	170	90
301770	4615740	30	26	48	67	163	90
301800	4615740	31	26	48	67	165	91
301830	4615740	33	26	48	66	168	89
301860	4615740	33	26	47	66	164	90
301890	4615740	34	25	45	65	165	90
301920	4615740	32	25	46	65	166	88

301950	4615740	32	25	47	65	165	88
301980	4615740	31	26	46	65	166	90
302010	4615740	30	27	48	67	165	90
302040	4615740	33	26	48	66	165	88
301710	4615710	37	29	53	71	177	97
301740	4615710	33	28	51	69	170	92
301770	4615710	32	26	49	68	167	91
301800	4615710	33	28	48	67	169	91
301830	4615710	31	25	47	67	166	92
301860	4615710	32	27	48	67	166	91
301890	4615710	33	27	48	68	169	91
301920	4615710	33	27	49	67	172	91
301950	4615710	34	26	50	66	170	92
301980	4615710	34	27	48	67	167	90
302010	4615710	34	27	50	67	167	91
302040	4615710	33	27	49	67	170	92
301710	4615680	36	31	51	72	179	94
301740	4615680	35	28	50	69	173	92
301770	4615680	36	28	49	67	166	92
301800	4615680	33	25	49	67	168	89
301830	4615680	32	27	46	66	170	94
301860	4615680	31	27	50	65	168	91
301890	4615680	33	25	48	66	168	90
301920	4615680	35	27	47	66	172	92
301950	4615680	34	28	50	66	170	92
301980	4615680	34	27	50	66	168	92
302010	4615680	35	27	49	68	171	93
302040	4615680	32	27	50	67	168	92
301710	4615650	33	30	50	68	174	97
301740	4615650	31	28	49	66	170	92
301770	4615650	31	27	49	66	165	89
301800	4615650	32	26	46	65	165	91
301830	4615650	32	27	47	65	164	89
301860	4615650	32	25	48	63	164	91
301890	4615650	32	25	46	64	164	91
301920	4615650	33	27	47	64	163	91
301950	4615650	32	27	47	65	168	91
301980	4615650	33	27	49	65	168	90
302010	4615650	33	26	48	65	167	91
302040	4615650	31	26	47	64	167	90
Average		33.00	26.85	48.68	66.61	168.43	91.44
Standard Deviation		1.61	1.23	1.64	1.69	3.53	1.95

Table A.15: Pixel values, average pixel value and standard deviation for control field on Landsat 5 image taken on May 4, 2005.

X	Y	B1	B2	B3	B4	B5	B7
301710	4615830	45	33	57	77	172	95
301740	4615830	46	31	56	76	171	92
301770	4615830	46	32	57	75	169	91
301800	4615830	47	33	57	76	170	90
301830	4615830	47	32	55	74	171	89
301860	4615830	46	31	52	73	168	91
301890	4615830	48	31	54	73	164	90
301920	4615830	45	31	55	75	169	93
301950	4615830	43	33	55	75	173	94
301980	4615830	43	33	55	75	174	95
302010	4615830	45	33	56	76	176	95
302040	4615830	43	31	54	74	174	94
301710	4615800	45	32	56	76	175	95
301740	4615800	45	30	56	74	167	90
301770	4615800	45	30	54	74	166	90
301800	4615800	45	32	56	75	169	93
301830	4615800	45	31	55	74	169	90
301860	4615800	44	30	53	73	168	92
301890	4615800	47	29	52	72	166	89
301920	4615800	44	31	53	73	167	91
301950	4615800	44	32	54	74	170	94
301980	4615800	44	32	55	74	173	95
302010	4615800	45	31	55	74	173	94
302040	4615800	43	31	54	74	172	94
301710	4615770	43	31	54	76	173	93
301740	4615770	42	30	54	74	169	91
301770	4615770	42	29	52	73	165	89
301800	4615770	43	30	53	72	162	90
301830	4615770	44	31	52	73	166	90
301860	4615770	43	30	53	72	165	91
301890	4615770	43	29	52	70	165	89
301920	4615770	40	30	52	71	165	91
301950	4615770	44	30	52	72	166	90
301980	4615770	42	30	52	72	165	93
302010	4615770	42	31	53	72	167	92
302040	4615770	44	30	53	72	167	92
301710	4615740	45	31	55	77	175	93
301740	4615740	44	30	53	74	170	90
301770	4615740	41	30	53	74	163	90
301800	4615740	42	30	53	74	165	91
301830	4615740	44	30	53	73	168	89
301860	4615740	44	30	52	73	164	90
301890	4615740	45	29	50	72	165	90
301920	4615740	43	29	51	72	166	88

301950	4615740	43	29	52	72	165	88
301980	4615740	42	30	51	72	166	90
302010	4615740	41	31	53	74	165	90
302040	4615740	44	30	53	73	165	88
301710	4615710	48	33	58	78	177	97
301740	4615710	44	32	56	76	170	92
301770	4615710	43	30	54	75	167	91
301800	4615710	44	32	53	74	169	91
301830	4615710	42	29	52	74	166	92
301860	4615710	43	31	53	74	166	91
301890	4615710	44	31	53	75	169	91
301920	4615710	44	31	54	74	172	91
301950	4615710	45	30	55	73	170	92
301980	4615710	45	31	53	74	167	90
302010	4615710	45	31	55	74	167	91
302040	4615710	44	31	54	74	170	92
301710	4615680	47	35	56	79	179	94
301740	4615680	46	32	55	76	173	92
301770	4615680	47	32	54	74	166	92
301800	4615680	44	29	54	74	168	89
301830	4615680	43	31	51	73	170	94
301860	4615680	42	31	55	72	168	91
301890	4615680	44	29	53	73	168	90
301920	4615680	46	31	52	73	172	92
301950	4615680	45	32	55	73	170	92
301980	4615680	45	31	55	73	168	92
302010	4615680	46	31	54	75	171	93
302040	4615680	43	31	55	74	168	92
301710	4615650	44	34	55	75	174	97
301740	4615650	42	32	54	73	170	92
301770	4615650	42	31	54	73	165	89
301800	4615650	43	30	51	72	165	91
301830	4615650	43	31	52	72	164	89
301860	4615650	43	29	53	70	164	91
301890	4615650	43	29	51	71	164	91
301920	4615650	44	31	52	71	163	91
301950	4615650	43	31	52	72	168	91
301980	4615650	44	31	54	72	168	90
302010	4615650	44	30	53	72	167	91
302040	4615650	42	30	52	71	167	90
Average		44.00	30.85	53.68	73.61	168.43	91.44
Standard Deviation		1.61	1.23	1.64	1.69	3.53	1.95

Table A.16: Pixel values, average pixel value and standard deviation for #1 control field on Landsat 5 image taken on September 9, 2005.

X	Y	B1	B2	B3	B4	B5	B7
298410	4616220	43	24	38	62	108	57
298590	4616040	48	26	45	56	99	53
298620	4616040	47	28	45	54	101	59
298590	4616010	46	26	44	56	99	55
298620	4616010	47	26	44	53	99	57
298590	4615980	45	25	43	55	101	57
298620	4615980	44	25	44	50	100	57
298590	4615950	46	25	43	55	99	57
298620	4615950	45	25	43	51	100	59
298590	4615920	45	27	45	56	98	57
298620	4615920	46	26	45	53	100	60
298590	4615890	45	26	44	55	101	57
298620	4615890	44	26	43	52	99	58
298590	4615860	45	27	46	57	101	57
298620	4615860	49	26	46	52	99	57
Average		45.67	25.87	43.87	54.47	100.27	57.13
Standard Deviation		1.59	0.99	1.92	2.92	2.34	1.64

Table A.17: Pixel values, average pixel value and standard deviation for #2 control field on Landsat 5 image taken on September 9, 2005.

X	Y	B1	B2	B3	B4	B5	B7
301200	4609080	50	32	51	75	130	73
301230	4609080	53	32	51	68	117	70
301260	4609080	52	33	51	64	113	71
301200	4609050	49	32	52	75	126	70
301230	4609050	52	33	52	73	125	69
301260	4609050	57	37	59	71	123	73
301200	4609020	48	30	47	76	119	67
301230	4609020	49	32	47	72	124	68
301260	4609020	52	33	53	68	112	66
301200	4608990	50	29	47	74	119	66
301230	4608990	50	30	49	70	116	62
301260	4608990	49	29	47	67	110	64
301200	4608960	49	29	46	74	117	63
301230	4608960	50	28	47	70	113	65
301260	4608960	50	30	48	66	110	65
301200	4608930	47	29	45	74	117	64
301230	4608930	51	30	48	67	112	63
301260	4608930	48	31	47	68	111	62
301200	4608900	46	31	48	74	122	65
301230	4608900	53	33	51	66	113	67
301260	4608900	49	30	47	70	113	65
301200	4608870	50	30	51	74	125	71
301230	4608870	52	34	52	68	118	68
301260	4608870	47	29	47	70	112	65
301200	4608840	46	28	46	72	116	66
301230	4608840	51	31	50	68	116	65
301260	4608840	50	30	48	66	112	63
301200	4608810	46	28	43	72	116	62
301230	4608810	52	31	49	66	108	62
301260	4608810	49	29	47	65	105	59
301200	4608780	46	28	44	74	118	63
301230	4608780	50	29	46	66	110	62
301260	4608780	48	30	46	66	106	59
301200	4608750	49	28	47	72	118	65
301230	4608750	51	31	49	66	108	61
301260	4608750	52	31	49	66	107	61
301200	4608720	51	30	50	69	125	73
301230	4608720	53	32	51	67	118	68
301260	4608720	52	31	49	64	108	63
301200	4608690	48	28	47	69	120	68
301230	4608690	52	31	50	68	117	67
301260	4608690	53	32	49	65	109	63
301200	4608660	45	28	44	72	117	65
301230	4608660	50	32	52	67	114	67

301260	4608660	51	32	50	67	110	66
301200	4608630	45	28	44	72	113	62
301230	4608630	52	32	52	67	115	68
301260	4608630	53	32	51	71	115	67
Average		49.96	30.58	48.67	69.40	115.38	65.56
Standard Deviation		2.48	1.91	2.91	3.36	5.75	3.48

Appendix B

Samples of Sewage Sludge Application Records

SITE STATUS REPORT
026.C

A. Information

This form is to be used to report cumulative annual sludge applications on a specific field. Report latest annual work within 90 days of last application. Report all previous years application since soil analysis.

Last soil analysis (date 11/1/84), (LBS/AC), Cd 4 Cu 100
Pb 208 Ni 72 Zn 278

Operator CITY OF OREGON Applicator CITY OF OREGON

Field I.D. **O26.C** Date Submitted 1/22/03

County LUCAS Sludge Source AEROBIC DIGESTER

Subsequent Applications month/day/year — Sludge Applied (dry tons/acre) — Metals Applied (lbs/acre)

Start	Finish	Acres	DT/Ac	Cadmium	Copper	Lead	Nickel	Zinc
1/1/1985	12/31/1985	12	4.8	0	2.7	2.7	1.1	5.3
1/1/1986	12/31/1986	12	4.4	0	2.5	1.3	1.7	4.5
1/1/1987	12/31/1987	12	2.7	0	1.6	0.7	0.2	2.7
1/1/1988	12/31/1988	12	6.2	0	4.5	1.2	0.6	8.4
1/1/1992	12/31/1992	12	3.0	0	1.8	0.5	0.2	4.3
1/1/1993	12/31/1993	12	4.0	0	3.1	0.7	0.3	6.2
1/1/1994	12/31/1994	12	2.5	0.1	2.3	1.0	0.2	4.4
1/1/1998	12/31/1998	12	12.1	0.1	9.1	2.6	0.9	20.1
1/1/2001	12/31/2001	12	1.2	0.01	1.0	0.2	0.1	1.6
1/2/2002	1/4/2002	12	1.32	0.007	1.0	0.2	0.1	1.8
Total in soil				4.22	129.6	219.1	77.4	337.3

A. Attach soil and tissue analysis (if necessary).
B. Attach log of any complaints received.
C. Was sludge incorporated as of the date of this report? YES
D. Status of field
1. Limiting factor NITROGEN-PHOSPHOROUS
2. Yearly limit of cadmium (lb/acre) 0.4

Figure B-1: Site status report for sewage sludge applied field 26C from Wastewater Treatment Plant, Oregon, Ohio

013A SITE STATUS REPORT

This form is to be used to report cumulative annual sludge applications on a specific field. Report all previous years applications.

	As	Cd[1]	Cr	Cu[1]	Pb[1]	Hg	Mo	Ni[1]	Se	Zn[1]
Last soil analysis (date [2]) (MG/KG),		0.2		19	19			18		75

Operator [redacted]

Field I.D. 013.A

County LUCAS

Applicator [redacted]

Date Prepared January 6, 2004

Sludge Source AEROBIC DIGESTER

Applications month/day/year		Sludge Applied (dry tons/acre)		Metals Applied (lbs/acre)									
Start	Finish	Acres	DT/Ac	Arsenic	Cadmium	Chromium	Copper	Lead	Mercury	Molybd	Nickel	Selenium	Zinc
Present in soil before any sludge application:					0.40		38	38			36		150
08/28/1990	10/31/1990	56	3.83		0.01	0.3	0.8	0.2	0.01		0.1		1.9
08/22/2003	08/28/2003	56	2.41	0.04	0.02	0.5	1.9	0.2	0.01	0.16	0.1	0.03	3.3
Total in soil				0.04	0.43	0.8	40.7	38.4	0.02	0.16	36.2	0.03	155.2
Cumulative Pollutant Loading Limits (lbs/Acre)				36	34	2634	1300	260	15	NA	370	89	2400

A. Attach soil and tissue analysis (if necessary).
B. Attach log of any complaints received.
C. Was sludge incorporated as of the date of this report? YES

[1]Data taken from Table 6, Page 6, of "Ohio Guide for Land Application of Sludge", Research Bulletin 1079, September 1982.

Figure B-2: Site status report for sewage sludge applied field 13A from Wastewater Treatment Plant, Oregon, Ohio

OhioEPA

Annual Sewage Sludge Report Form

DIVISION OF SURFACE WATER

[redacted]

Table 2 Continued: Sewage Sludge Constituents

Please Type

Facility Name:	Date:
City of Oregon Wastewater Treatment Plant	2/11/2004

OEPA Permit #:	NPDES Application #:
2PD0035*GD	OH0052914

Values Reported for Calendar Year 2003

		00627 TKN (mg/kg)	00611 NH3-N mg/kg	00668 P mg/kg	00938 K (mg/kg)	00400 pH (S.U.)	70318 TS (%)	70322 VS (%)	70316 Sludge Wt. (dry tons)
Jan	Max								
	Avg								
	Min								
Feb	Max								
	Avg								
	Min								
Mar	Max								
	Avg								
	Min								
Apr	Max	63,500	9,010	26,200	3,040	7.3	2.89	65	
	Avg	63,500	9,010	26,200	3,040		2.89	65	1.45
	Min	63,500	9,010	26,200	3,040	7.3	2.89	65	
May	Max								
	Avg								
	Min								
June	Max								
	Avg								
	Min								
July	Max								
	Avg								
	Min								
Aug	Max	78,000	27,400	40,900	3,670	8.0	3.93	60	
	Avg	78,000	27,400	40,900	3,670		3.42	56	281.91
	Min	78,000	27,400	40,900	3,670	7.5	3.18	53	
Sept	Max	55,200	16,100	37,500	3,180	8.2	4.54	53	
	Avg	55,200	16,100	37,500	3,180		3.69	51	266.46
	Min	55,200	16,100	37,500	3,180	7.5	2.13	39	
Oct	Max								
	Avg								
	Min								
Nov	Max								
	Avg								
	Min								
Dec	Max								
	Avg								
	Min								
Total	Max	78,000	27,400	40,900	3,670	8.2	4.54	65	
	Avg	65,567	17,503	34,867	3,297		3.33	57	549.82
	Min	55,200	9,010	26,200	3,040	7.3	2.13	39	

Figure B-3: A page of annual sewage sludge report from, from Division of Surface Water, Ohio EPA